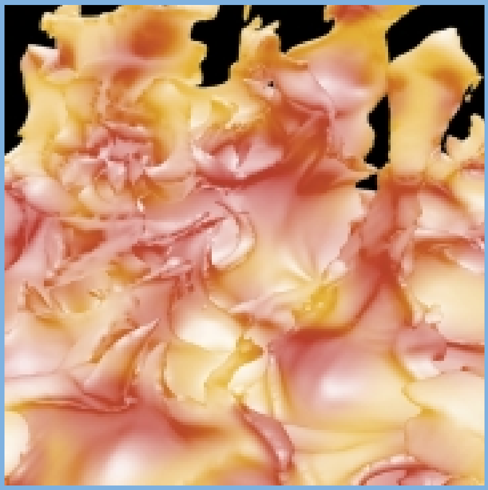
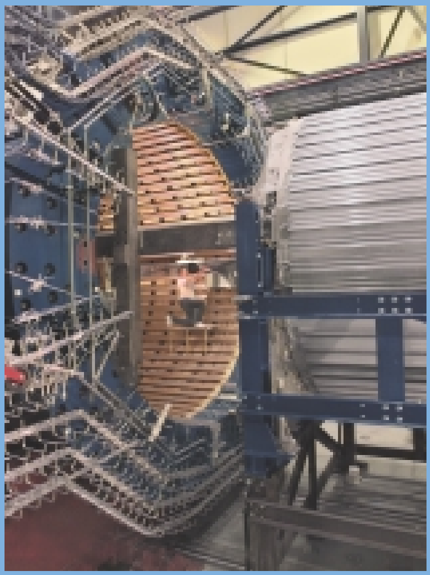
SCIENCE PORTFOLIO

Fuel the Future

Provide Extraordinary Tools





Protect Our Living Planet

Explore Matter and Energy

OFFICE OF SCIENCE

U.S. Department of Energy

ABOUT THE OFFICE OF SCIENCE

The Department of Energy's Office of Science funds basic research to advance the scientific knowledge needed to provide new and improved energy technologies; to understand the health and environmental implications of energy production and use; and to maintain U.S. leadership in discovering the fundamental nature of energy and matter. As part of its mission, the Office of Science plans, constructs, and operates major scientific user facilities to serve researchers at universities, national laboratories, and industrial laboratories. The Office sponsors thousands of research projects at hundreds of scientific institutions across the United States, including investments in graduate research and education to ensure the next generation of highly capable scientists and engineers.

This *Strategic Plan* and the accompanying *Science Portfolio* advance the Department's missions through a set of crosscutting strategic goals, objectives and strategies—elements that bring focus to the multidisciplinary challenges that lay ahead. Supporting this crosscutting framework are the scientific disciplines embodied within the Office of Science that are collectively represented by its major research programs and subprograms, as noted below:

Advanced Scientific Computing Research
- *Mathematical, Information, and Computational Sciences*
- *Advanced Energy Projects and Technology Research*

Basic Energy Sciences
- *Materials Sciences*
- *Chemical Sciences*
- *Engineering and Geosciences*
- *Energy Biosciences*

Biological and Environmental Research
- *Life Sciences*
- *Medical Sciences*
- *Environmental Sciences*

Fusion Energy Sciences
- *Science*
- *Facility Operations*
- *Enabling R&D*

High Energy and Nuclear Physics
- *High Energy Physics*
- *Nuclear Physics*

Strategic Plan of the Office of Science

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About the Cover

A shockwave exploding through the interface of two fluids provides visual insight into the turbulent disorder of combustion (Goal 1—Fuel the Future). In a hardwood forest ecosystem in Tennessee, a complex of instrumented towers enables researchers to simulate the environment of the future with controlled releases of carbon dioxide (Goal 2—Protect Our Living Planet). The most distant and ancient galaxies visible from Earth in this representative slice of the night sky sprang from the fundamental particles and forces of the Big Bang (Goal 3—Explore Matter and Energy). The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will enable scientists to explore some of the most fundamental forms of matter, including the quark-gluon plasma (Goal 4—Provide Extraordinary Tools for Extraordinary Science).

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Goals and Objectives

PREFACE

The Department of Energy's Office of Science *Strategic Plan* is part of a long-range planning process to define its goals, objectives, strategies, and the portfolio of research it sponsors to advance the Department's mission. The *Plan* had its genesis in 1998 with the convening of two workshops, each attended by over 100 scientific professionals from universities, national laboratories, and industry. Their charge was to define the scientific challenges, research themes, and goals appropriate to the Office of Science, and to identify more specific objectives and strategies to achieve these goals. Posed within the pages of the resulting *Strategic Plan* are bold new questions and intriguing scientific challenges—on what we need to do to build scientific foundations for a strong and prosperous nation in the 21st century.

The scientific directions described in this *Plan* are further supported by a companion document, the *Science Portfolio*. The *Portfolio* provides the definitive link between the goals and strategies articulated in the *Plan* and the activities encompassed within our programs and budget structure. The *Portfolio* identifies recent scientific accomplishments and defines more detailed research activities to be conducted over the next few years. The resulting combined effort is part of an ongoing process that is shaping the Office of Science's approach to planning. Scientific advancements can never be fully planned, of course; but wise preparation establishes the conditions for discovery. As Louis Pasteur remarked, "Chance favors only the prepared mind." In this context, it is with gratitude that we acknowledge the many minds that contributed substantially to this effort and its underlying approach.

The preparation of this document was coordinated by the Office of Planning and Analysis, Office of Science. Questions may be addressed to: Director, Office of Planning and Analysis; 1000 Independence Avenue, S.W., Washington DC, 20825-0118; Phone: (202) 586-9942; Web site: www.er.doe.gov

INTRODUCTION

Articulating a widely held view, the National Academy of Sciences notes that much of this country's economic growth, quality of life, and security derives from national investments and leadership in science and technology. The nation's standard of living and prosperous technology-based economy are thus linked to our willingness to invest significant public resources to secure societal benefits not attainable by the normal workings of the marketplace.

The Department of Energy (DOE) is the third-largest government sponsor of basic research in the United States, principally through programs managed by the Office of Science. The mission of the Office of Science is

> *To advance basic research and the instruments of science that are the foundations for DOE's applied missions, a base for U.S. technology innovation, and a source of remarkable insights into our physical and biological world and the nature of matter and energy.*

In service to DOE's applied missions in energy resources, environmental quality, and national security, Office of Science programs lead the nation in many areas of the physical and computational sciences, and contribute significantly to major advances in biological research. These programs extend the frontiers of basic scientific knowledge—DOE and its predecessor agencies have supported the award-winning scientific research of 68 Nobel Laureates from 1934 through 1998.

Accelerators, light sources, neutron beam facilities, plasma and fusion science facilities, genome centers, and advanced computational centers are just some of the major instruments of science that distinguish DOE's capabilities and enhance the nation's science base and infrastructure.

Science for the Future: The Planning Context

The 20th century has brought many scientific advancements that have resulted in dramatic changes in the products of commerce and communications technologies, and in the diagnosis and treatment of disease. We are learning to control matter at the atomic level, develop cleaner energy sources, and look deeply into the cosmos to the origins of matter and energy. Business can now be conducted worldwide with a few strokes of a keyboard as a direct result of communications protocols developed by the computing sciences and high energy physics communities, research in which DOE has played a key role.

Affordable, abundant energy has been the cornerstone of our strong economy, and population growth and industrialization will greatly increase the world's use of energy.

Yet conventional energy sources are inevitably limited, and they often have significant environmental consequences on a local, regional, and global scale. Basic research is essential to create energy technologies that can provide new fuels, seek out new supplies of traditional fuels, convert known fuels to more effective forms, generate, store, and transmit electricity with less waste, and find more efficient ways to use energy.

Fundamental science is also needed to track pollutants through their intricate interactions with the environment and to uncover new ways to dispose of toxins and climate-changing greenhouse gases. Advances in scientific computation can be used to convert new knowledge and vast amounts of data into better models of global climate in order to predict the consequences of energy use and to test mitigation strategies. Unraveling the human genome and understanding the cellular environment can provide the knowledge necessary to improve the diagnosis and treatment of disease and to further protect human health. And if the nation's future is to be more secure, new approaches are required to detect and analyze chemical, biological, and nuclear threats rapidly. Understanding these complex challenges will require cross-disciplinary approaches.

Many other factors influence and provide the context for long-term science planning at DOE. For example, industry's emphasis on near-term payoffs challenges the nation to develop strategies for the long-term fundamental research essential to sustain innovation. There is an additional trend toward international collaboration on large, fundamental science projects, and the Internet—a tool for scientific communication—better connects the science community and opens the door to remote-controlled experimentation.

Federal science programs are being called upon to deliver more for less. The Government Performance and Results Act (GPRA) of 1993 establishes a supportive policy for planning and performance measurement that focuses on results. Managers and scientists must scrutinize their investments and establish their priorities more carefully than ever before.

Planning Approach

In developing this strategic plan, the Office of Science held two planning workshops, the first to form the overarching themes and the second to develop more focused goals, objectives, and strategies. Leading scientists, technologists, high-tech managers, science communicators, and futurists all participated, representing academic institutions, private business and industry, and DOE's own offices, facilities, and national laboratories. The workshop teams were encouraged to think beyond existing scientific organizations, disciplines, and agendas.

A unanimity of themes emerged from the first workshop. Among these were providing the scientific foundation for: improved fuels and power for an energy-efficient future; cleaning up the environment, preventing waste and pollution, and protecting human health; discovering the answers to the basic secrets of the universe, from the organization of life to the fate of the cosmos; and providing the necessary tools to enable cutting-edge scientific research.

The second workshop was held to generate ideas for the more specific components of this strategic plan. After consideration and refinement of the workshop results by DOE staff, the structure of this strategic plan took shape. Five central goals emerged:

- Fuel the future—science for clean and affordable energy
- Protect our living planet—energy impacts on people and the biosphere
- Explore matter and energy—building blocks from atoms to life
- Provide extraordinary tools for extraordinary science—national assets for multidisciplinary research
- Manage as stewards of the public trust—scientific and operational excellence

The first three goals address fundamental research directions that support the most urgent DOE priorities of the next 20 years. The fourth goal, "extraordinary tools for extraordinary science," identifies the critically important tools of discovery necessary to achieve the scientific research goals. Our fifth goal addresses the need for excellence in the management, planning, and execution of our programs.

We adopted ideas for combining program elements to address emerging areas of science, thus linking research areas to transcend the boundaries of individual disciplines. For example, the goal of exploring matter and energy has been extended to consider the formation of the building blocks of life and the science of complex and adaptive systems. The objectives and strategies address specific national challenges and opportunities, such as the need for carbon sequestration research and for advancing the state of scientific simulation as a tool for scientific discovery.

How do we determine whether we are achieving our objectives and attaining our goals? The merits of our research programs must be measured by the accomplishments of the scientists and engineers whom we support and the significance of those accomplishments in achieving the objectives of this strategic plan, and by our progress in sustaining the scientific resources of the nation. This document concludes by listing examples of such indicators of performance.

STRATEGY AT A GLANCE

GOAL 1. FUEL THE FUTURE—
Science for Clean and Affordable Energy

Objective 1. New Fuels: Advance the science for the development of new and improved sources of domestic fuels.

Strategies: ◗ *Chemistry and materials science for energy conversion* ◗ *Plant, microbial, and solar conversion research* ◗ *Geosciences*

Objective 2. Clean and Affordable Power: Explore the science that will lead to advanced generation, storage, and transmission of electricity.

Strategies: ◗ *Metals, ceramics, and condensed matter physics* ◗ *Electrochemical sciences* ◗ *Plasma science and fusion research*

Objective 3. Efficient Energy Use: Develop the scientific foundations for cleaner, safer, and more efficient energy use.

Strategies: ◗ *Combustion science* ◗ *Advanced materials for efficiency* ◗ *Engineering sciences* ◗ *New catalysis and chemical transformations*

GOAL 2. PROTECT OUR LIVING PLANET—
Energy Impacts on People and the Biosphere

Objective 1. Sources and Fate of Energy By-products: Improve our scientific understanding of the sources and fate of energy by-products.

Strategies: ◗ *Sources and transport in the biosphere* ◗ *Chemical interactions and transformations*

Objective 2. Impacts on People and the Environment: Provide a basic understanding of the biology and ecology of energy by-products as they affect humans and the natural world.

Strategies: ◗ *Human health impacts and risks* ◗ *Ecosystem and biological responses* ◗ *Regional and global consequences*

Objective 3. Prevention and Protection: Create new science-based approaches to minimize energy by-products and protect the biosphere and human health.

Strategies: ◗ *Pollution minimization* ◗ *Cleanup and remediation* ◗ *Carbon sequestration* ◗ *Health protection and medical research*

GOAL 3. EXPLORE MATTER AND ENERGY—
Building Blocks from Atoms to Life

Objective 1. Components of Matter: Understand the nature of matter at the most fundamental level.

Strategies: ◗ *Elementary particles and their interactions* ◗ *Nuclear matter and interactions* ◗ *Atoms and molecules* ◗ *Biomolecular building blocks*

Objective 2. **Origin and Fate of the Universe: Explore the evolution and fate of the universe through the fundamental interactions of energy, matter, time, and space.**

Strategies: ◗ *Beginning of the cosmos* ◗ *Creation of nuclei and matter* ◗ *Evolution of astrophysical structures* ◗ *Formation of life*

Objective 3. **Complex Systems: Control complex systems of matter, energy, and life.**

Strategies: ◗ *Complex phenomena* ◗ *Adaptive systems*

Goal 4. Provide Extraordinary Tools for Extraordinary Science— National Assets for Multidisciplinary Research

Objective 1. **Instrumentation for the Frontiers of Science: Provide leading research facilities and instrumentation to expand the frontiers of the natural sciences.**

Strategies: ◗ *Accelerators and detectors for high-energy and nuclear physics* ◗ *Light sources and neutron beam facilities* ◗ *Specialized scientific facilities*

Objective 2. **Scientific Simulation: Advance computation and simulation as critical tools for scientific discovery.**

Strategies: ◗ *Science applications software* ◗ *Ultra-high performance computation and communications facilities* ◗ *Computer science and enabling technologies*

Objective 3. **Institutional Capacity: Strengthen the nation's institutional and human resources for basic science and multidisciplinary research.**

Strategies: ◗ *National laboratory system* ◗ *Disciplines essential to our missions* ◗ *Science education* ◗ *Broadening the scope of research performers*

Goal 5. Manage as Stewards of the Public Trust— Scientific and Operational Excellence

Objective 1. **Scientific Excellence and Mission Relevance: Pursue the highest standards of scientific excellence and relevance.**

Strategies: ◗ *Peer review and merit evaluation* ◗ *Scientific advice and planning* ◗ *Research coordination and partnerships* ◗ *Culture for creativity*

Objective 2. **Protect Workers, the Public, and the Environment: Distinguish our facilities and operations as models of safety, health, and environmental protection.**

Strategies: ◗ *Integrated Safety Management* ◗ *Communications and community relations*

Objective 3. **Management Effectiveness and Efficiency: Manage our operations and human resources for high performance and efficiency.**

Strategies: ◗ *Performance-based management* ◗ *Streamlined operations* ◗ *Award-winning construction management practices* ◗ *Trained and effective work force*

A shockwave exploding through the interface of two fluids, simulated at the National Energy Research Scientific Computing Center, provides visual insight into the turbulent disorder of combustion. Turbulence at the flame front can accelerate combustion, improving efficiency and reducing pollution.

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Fuel the Future

SCIENCE FOR CLEAN AND AFFORDABLE ENERGY

AMERICA HAS BEEN A NATION RICH IN NATURAL RESOURCES. BUT NOW, CHALLENGES FOR THIS AND SUCCESSIVE GENERATIONS ARISE FROM EXHAUSTIBLE SUPPLIES OF ENERGY AND AN ENVIRONMENT SHOWING IMPACTS OF ENERGY BY-PRODUCTS. OUR BASIC RESEARCH AIMS TO DISCOVER FUNDAMENTALLY NEW SOURCES OF ENERGY, AND PROCESSES AND PHENOMENA THAT ARE INHERENTLY MORE EFFICIENT AND ENVIRONMENTALLY BENIGN. WITH A SENSE OF RESPONSIBILITY AND OPTIMISM, THE NATION'S SCIENTISTS CREATE THE KNOWLEDGE THAT BRINGS FORTH NEW CONCEPTS AND SOLUTIONS.

Abundant energy has been a key to our nation's economic success and a hallmark of our standard of living—a fact too easy to forget during these times when gasoline and electricity prices are relatively low.

While we in the United States make up less than a twentieth of the world's population, we consume more than a fifth of the world's energy. At the same time, four-fifths of the world's people live in developing nations and consume only a third of the energy; most are eager to use more to improve their standard of living. For example, in its determined move to prosperity, populous China, a net exporter of oil until late in 1993, now imports over half a million barrels of oil a year.

Producing and using energy costs more than money. Pollution and other by-products affect human health, air quality, and the world's climate. By-products of energy use can corrode metal and paint, and adversely affect the ecology of lakes, streams and forests.

The challenge of providing the nation with a secure energy supply and devising ways to use energy more efficiently and less harmfully is a fundamental scientific challenge. Through research programs at universities and national laboratories, and in cooperation with private industry, the Office of Science progresses toward three critical objectives:

1. To discover new chemical and biological processes, and the advanced materials necessary to supply tomorrow's energy demand, and understand geological phenomena that can extend fuel reserves
2. To develop the scientific foundations for improved utilization of electric power through more efficient generation, storage, and transmission
3. To bring to bear a variety of basic sciences to improve the efficiency of energy use in every aspect of our lives, from factories to home lighting

While the science is basic, the task of securing clean, affordable energy for the future could not be more practical or more urgent.

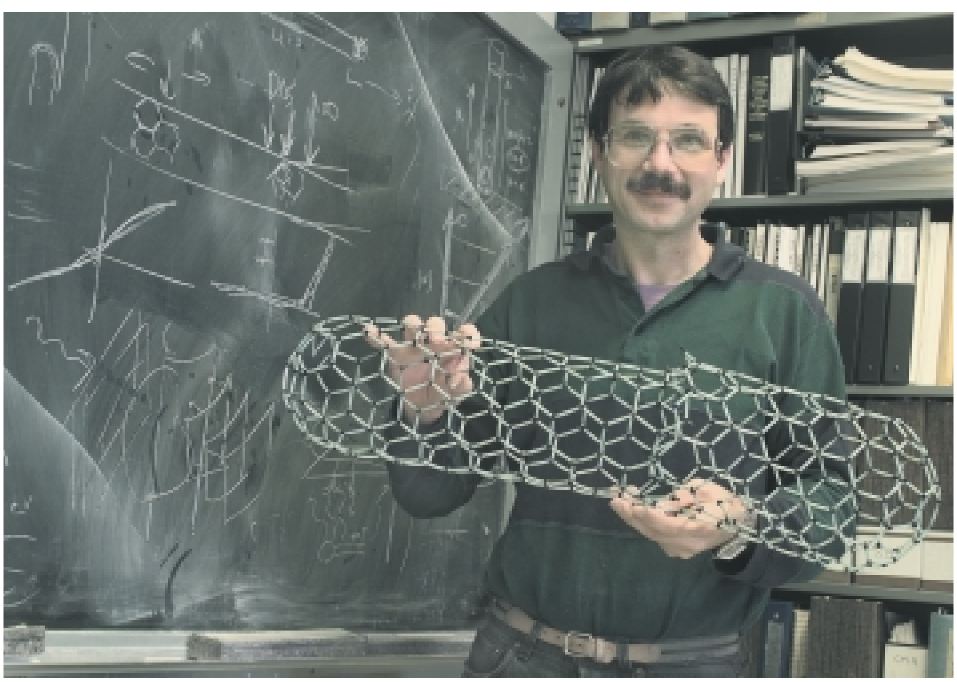
NEW FUELS

OBJECTIVE 1: ADVANCE THE SCIENCE FOR THE DEVELOPMENT OF NEW AND IMPROVED SOURCES OF DOMESTIC FUELS

The nation approaches a future in which new kinds of fuel and new forms of energy must supply an increasing proportion of our energy consumption, even as scientists today devise new methods for finding and recovering fossil fuels. Advancing the science for the development of new and improved sources of domestic fuels is a multifaceted objective, and to help achieve it the Office of Science has adopted three strategies.

The first is to support advances in chemistry, physics, and materials science needed for the conversion of crude hydrocarbons into cleaner fuels. The second strategy concentrates on new areas of the biological sciences—probing the molecular and cellular processes of plants and microbes to produce new biofuels and learning the secrets of photosynthesis to imitate it. The third strategy calls for advances in geoscience: the discovery and characterization of remaining deposits of fossil fuels require that mathematics and computation unite with mineralogy and new exploratory probes to visualize what's under the land and sea in more vivid and informative ways.

The carbon nanotube model held by this Lawrence Berkeley National Laboratory scientist represents a structure only billionths of a meter in diameter. Nanotubes are chemically inert, 100 times stronger than steel, and have a range of unique electrical, thermal, and structural properties.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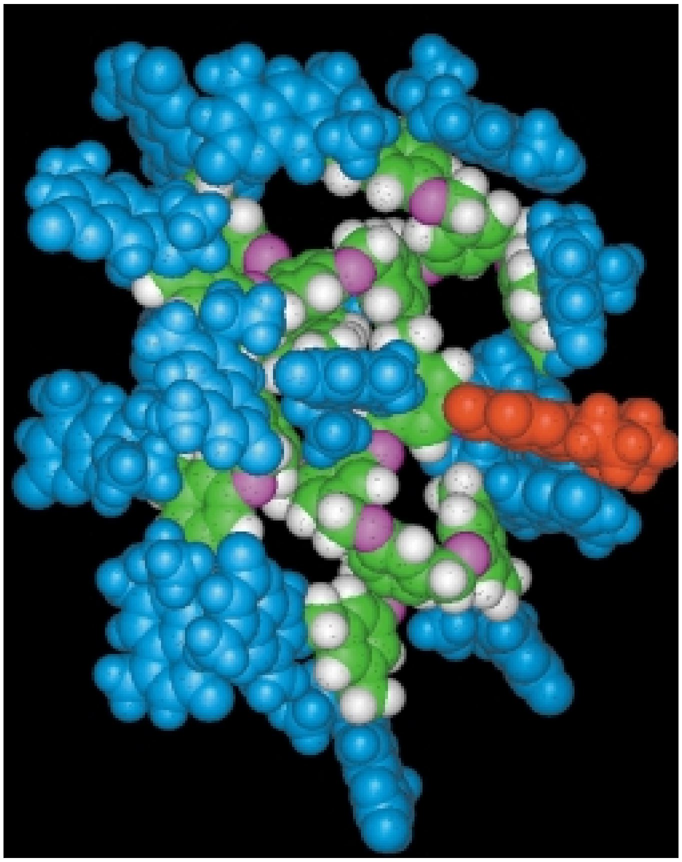
Chemistry and materials science for energy conversion

Very few fuels come out of the ground—or the field or the forest—ready to burn, and traditional fuels may not be the best for the future. Basic research helps us understand how to convert crude fuels to cleaner, more efficient forms—an essential goal—and may also reveal new kinds of fuels and previously untapped sources of energy.

More effective and selective catalysts and reaction pathways are needed to convert abundant domestic supplies of fossil fuels into cleaner burning, higher-energy liquid and gaseous fuels. Advanced catalysis, electrochemistry, new sensors and controls, new materials for refining and separation, and computer simulation and design can contribute to more effective conversion of hydrocarbons. Research also focuses on new sources of hydrocarbons, such as the crystalline solids known as methane hydrates, found in ocean floor sediments. The energy content of these methane hydrates may be twice that of the other fossil fuels known to exist.

Hydrogen is one of the future's most promising fuels; it can be burned directly, for example in nonpolluting vehicles, or converted to electricity in fuel cells. Methods for producing hydrogen include reforming natural gas, photocatalytic dissociation of water, heat treatment of waste, and hydrogen-producing microorganisms. Continued research on new catalysts and enzymes offers the promise of making these methods more efficient. In addition, ways to store hydrogen inexpensively and safely are a matter of intense research interest.



Frechet Group, UC Berkeley

Seeking to mimic—and improve—the efficient molecular methods that plants, algae, and photosynthetic bacteria have evolved to harvest energy from sunlight, researchers assemble functional macromolecules from molecular sub-units possessing specific catalytic, photochemical, or biological properties, such as this light-harvesting dendrimer.

Plant, microbial, and solar conversion research

Biomass is a renewable, versatile, and increasingly practical fuel source. Through research we seek to improve the productivity of crops, engineer new plant forms, and understand the crucial role of microorganisms in converting biomass to fuel.

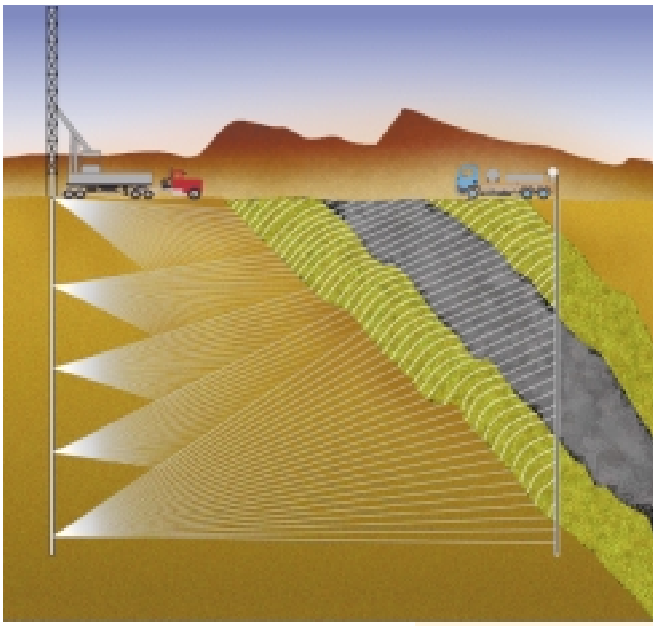
Understanding metabolic pathways will increase our ability to improve plant productivity and resistance to stress. New chemical and photochemical catalysts and enzymes will make possible the efficient conversion of biomass to gaseous and liquid fuels that can be cleanly converted to energy. Using genetically engineered crops to produce fuels more directly will also be researched.

The study of newly discovered microbes and microbial communities is a burgeoning field of research, which includes fermentation in the absence of oxygen, high-temperature survival and growth, and the phenomenon of photosynthesis in bacteria. A fundamental understanding of photosynthesis in plants and microbes is an important research goal itself. In terms of fueling the future, we may be able to develop artificial photosynthesis and mechanisms to convert sunlight directly to chemical energy.

Geosciences

The nation's overwhelming dependence on traditional supplies of coal, oil, and natural gas will likely persist into the middle of the next century. Geophysical and geochemical research seeks to identify fluids (including oil and gas deposits) and understand their flow through geologic media; advanced software can improve the analysis of new data and also "mine" data on known hydrocarbon reservoirs accumulated during decades of exploration and production. Research into revolutionary seismic and electromagnetic methods of imaging should provide clearer pictures of the underground, including the types of fluids present.

Geoscientific research supported by the Office of Science focuses on more than hydrocarbons. We will continue to investigate the geophysical and geochemical bases that underlie the exploration for geothermal systems, and to map the types of pollutants and salinity present in groundwater aquifers.



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In an experimental imaging technique, EM tomography, a transmitter sends low-frequency electromagnetic signals from various depths in a borehole to a receiver in a second borehole. From the arrival times of the signals, a computer creates a tomogram, mapping underground structures according to differences in their resistivity.

Underground Imaging

Finding and characterizing mineral resources deep in the earth have always been scientific and technological challenges. Of the numerous techniques used to characterize oil and gas reservoirs, whether taking samples right from the borehole or making long-range seismograms, all are limited in range or resolution.

One technique uses electromagnetic signals, the reception strength of which varies according to the electrical resistivity of the material through which they travel. Oil-bearing sand, for example, can be ten times as resistive as clay or carbonates.

While electromagnetic energy propagates without loss in free space, the ground attenuates the signal severely, especially at high frequencies. Away from measurement points, the spatial resolution of resistivity is limited, and drilling boreholes close together for better resolution is prohibitively expensive.

Researchers have recently discovered a mathematical transformation that converts diffuse electromagnetic signals into "wavefields" similar to those used in seismograms. A resistivity image is constructed using the transformed wavefield's travel times. This allows better images to be constructed at greater range, which will improve the understanding of the subsurface environment and potentially reduce drilling costs.

OBJECTIVE 2: EXPLORE THE SCIENCE THAT WILL LEAD TO ADVANCED GENERATION, STORAGE, AND TRANSMISSION OF ELECTRICITY

Over a third of the energy consumed in the United States is electric, the bulk of it produced by burning coal or other fossil fuels. The Office of Science supports basic research dedicated to generating electricity with greater efficiency and less impact on the environment, and to storing and distributing electricity with fewer losses. We have adopted three strategies to meet this objective: to foster advances in metals, ceramics, and condensed-matter physics; to promote research in the electrochemical sciences; and to emphasize plasma science and fusion research.

ORNL

A scientist measures metallic layers deposited by a robot-mounted plasma spray gun. Plasma spraying is one of a number of thermal spray capabilities being developed to apply advanced coatings that can withstand heat, wear, corrosion, and chemical reactions. These processes, being developed at Oak Ridge National Laboratory, can also be used to create free-standing structures or multilayer materials.

Metals, ceramics, and condensed matter physics

Advanced materials are crucial to more efficient generation of electricity from all sources, whether by burning fuel in turbines and boilers; converting the energy of sunlight, wind, and running water; or tapping current from the chemical processes in fuel cells and batteries.

New and improved metals and ceramics that can withstand very high temperatures and severe chemical and mechanical stresses are essential for technological innovation and efficiency improvements in turbines and boilers. Materials science may enable the development of advanced gas turbines that will achieve efficiency far greater than the best turbines today and power plants that will generate electricity from many fuels, including liquefied or gasified coal and biomass, with dramatic increases in overall output.

Research will improve our understanding of the fundamental properties of semiconductors, enable the discovery of new photoelectric materials, and find physical and chemical means to control impurities for cheaper, more efficient solar cells. Already, experimental photovoltaics have achieved efficiencies of 30 percent, half again as efficient as present solar cells. Electricity and heating from thermal solar energy will depend on new high-temperature materials and basic studies of light-matter interactions under conditions of brightness and heat.

Fundamental research is vital for developing the novel magnetic materials and new technologies needed for storing and controlling electricity, and for transmitting it with less loss. For example, the phenomenon of high-temperature superconductivity still eludes basic theoretical explanation, but basic research on high-temperature superconducting materials may someday enable the economic fabrication of cables that will transmit electricity over long distances without loss. Superconducting magnetic storage devices promise to hold large currents, supercapacitors and advanced batteries could store energy effectively for many applications, and devices based on new magnetic materials may improve the control and distribution of electric current.

A materials scientist at Oak Ridge National Laboratory uses electron-beam evaporation to deposit buffer layers on a nickel substrate, novel steps in the fabrication of new superconducting wire materials.

ORNL

Electrochemical sciences

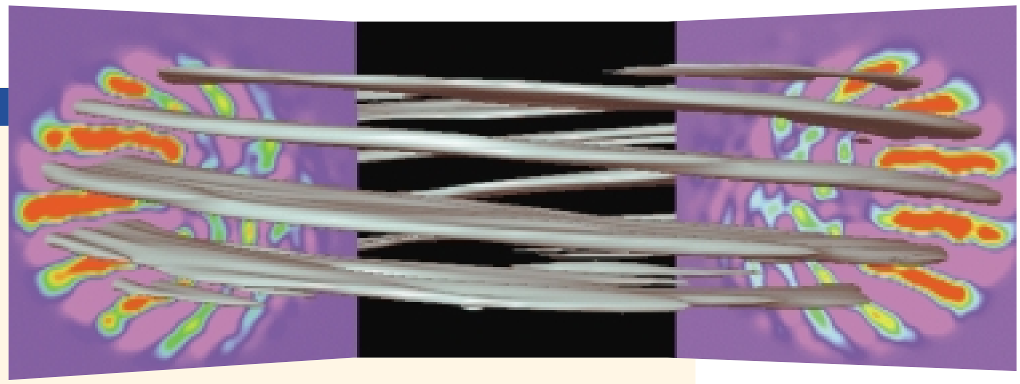
New liquid, solid, and thin-film electrolytes offer many improvements in batteries, including safe operation at high temperatures, safe, persistent rechargeability, lighter weight, and higher energy densities. New chemical processes will be investigated to improve batteries and fuel cells, which deliver electricity through chemical processes. Future applications of these scientific advances include industrial-scale fuel cells, hybrid vehicles, and portable power for buildings.

Plasma science and fusion research

Plasma science and other studies of fusion offer the prospect of abundant and clean electricity, tapping a virtually inexhaustible supply of fuel in the form of heavy hydrogen isotopes contained in ordinary water.

Magnetic and inertial confinement are the two most basic schemes for controlling fusion in reactors. The former uses magnetic fields to contain a hot plasma; the latter implodes small pellets of fuel with pulses of power from lasers, x-rays, or ion beams. Within these general categories are a wide variety of innovative concepts, including a levitated superconducting dipole experiment and the implosion of magnetized plasma targets.

Fusion



Dr Scott Parker, University of Colorado, Boulder/LANL

This plasma simulation model performed by University of Colorado scientists shows the electrical gradient (colored planes) in the instability of the plasma just before transition to turbulence.

In fusion, the nuclei of two hydrogen isotopes are combined to form a helium nucleus, thereby releasing a large amount of energy. Unlike fission, the potential fuel supply for fusion is virtually inexhaustible, and the dangers of radiation and radioactive waste much less.

So far, sustained fusion reactions have been observed only in stars. There, gravity confines the hydrogen fuel. To control fusion on Earth, hydrogen must be compressed to high densities and heated to hundreds of millions of degrees. One approach, the tokamak magnetic fusion concept, confines the plasma with intense magnetic fields, then heats it with electric currents, radio waves, or beams of neutral particles. This approach has been successful in producing over 16 million watts of fusion power for short periods of time—about one second. Another approach, inertial fusion, proposes to use beams of energy to implode small beads of hydrogen fuel so rapidly and consistently that power could be obtained in a quasi-continuous fashion. Research continues on many scientific fronts aimed at achieving a sustainable reaction that would open the door to an important new, clean energy source.

Basic scientific questions of heat transfer and power conversion remain for all fusion reactor designs. One area of research—which also applies to the safety and dependability of fission reactors—concentrates on how radiation, particularly intense neutron bombardment, degrades materials through corrosion, cracking, and embrittlement. A related approach, posing intriguing science and technology questions, focuses on reactor walls made of liquid metal.

Whether the turbulence in hot plasmas can be controlled, whether the pulsed-power systems needed for inertial confinement can be made sufficiently durable, and whether materials can be created to withstand the continued stress of heat, radiation, and microexplosions are all questions that call for investigation, and the pursuit of plasma and fusion science.

OBJECTIVE 3: DEVELOP THE SCIENTIFIC FOUNDATIONS FOR CLEANER, SAFER, AND MORE EFFICIENT ENERGY USE

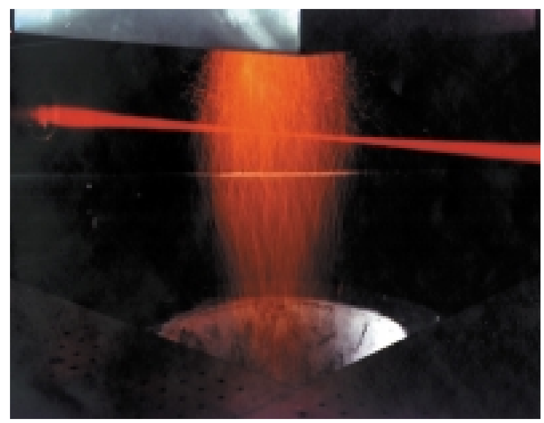
Using less energy by using it more efficiently may benefit society even more than finding new fuels or new ways of producing electricity. The Office of Science addresses this complex task by supporting basic research in many disciplines and encouraging collaborations among researchers from universities, national laboratories, and private industry. Our strategies for achieving this objective promote research in four areas: combustion science, advanced materials for efficiency, engineering sciences, and catalysis and chemical transformations.

Combustion science

Combustion is the primary means of converting energy stored as chemical bonds in fuel into kinetic energy for work. With the aid of new experimental methods, advanced computer modeling, and leading-edge instrumentation such as laser frequency-modulation spectroscopy, studies in reaction dynamics and fluid mechanics seek to provide the basis for improving efficiency and reducing waste emissions in internal combustion engines, furnaces, electric utility turbines and burners, and industrial plants.

Advanced materials for efficiency

Basic research examines the microstructural aspects of behavior in materials, with far-reaching implications for energy generation, transmission, conversion, and conservation technologies. For example, research into lighter and stronger structural materials, and new metals, ceramics, and polymers—for fuel cells, batteries, high-temperature engines, microturbines, and high-speed flywheels—can revolutionize the design of cars, trains, ships, aircraft, and other vehicles for personal and mass transit.



Sandia

Modeling and simulation capabilities augment lasers and other means of studying alternative fuels, chemical reaction pathways, and novel engines and burners at the Combustion Research Facility at Sandia National Laboratories in California.

Thin-film and semiconductor research will make it possible to use bright light-emitting diodes instead of incandescent or fluorescent light bulbs—as well as photochromic and electrochromic window coatings, new construction materials such as virtually weightless aerogel insulators, and other innovations that can also markedly reduce energy use in residences and commercial buildings.

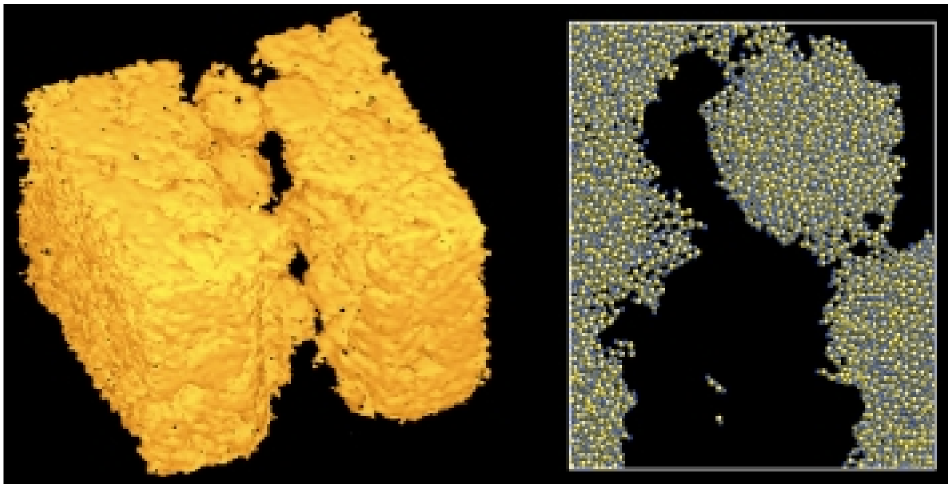
Nanotechnology, self-assembling polymers, and ion implantation are some of the approaches that can revolutionize materials science and introduce energy-saving manufacturing methods and more efficient new products to the microelectronics industry.

These and numerous other advances will continue to be the fruits of fundamental research into the chemical, physical, electrical, optical, and thermodynamic properties of materials, from nanoscale clusters to commodities in bulk, promising astonishing progress in energy efficiency.

Engineering sciences

Continual monitoring and adjustment is essential to the energy efficiency of numerous processes, from heating and lighting to internal combustion to large-scale industrial processes. Sensors and controls must be able to operate in extreme physical and chemical environments, instantly signaling change for precise and rapid response.

Basic research will pursue new laser and fiber-optic systems that resist electrical interference while measuring chemical concentrations in harsh factory environments. Artificial diamond sensors may be engineered to withstand hot flue gases. Research will seek to engineer biological cells in combination with microcircuitry to form biosensors that detect low chemical concentrations, for monitoring biomass conversion and other processes. These and other concepts for advanced sensors and controls will be the subject of scientific investigation that will pave the way for more efficient energy use and innovative pollution prevention processes.



Dr Rajiv K. Kalia, Louisiana State University/ANL

Nanophase silicon nitride is predicted to be a ceramic 10 times tougher than conventional coarse-grained materials. Its behavior can be studied through massively parallel computer simulations of the component forces of individual silicon (blue) and nitrogen (yellow) atoms. This research at Louisiana State University and Argonne National Laboratory shows how the fine atomic clusters slow the spread of fractures.

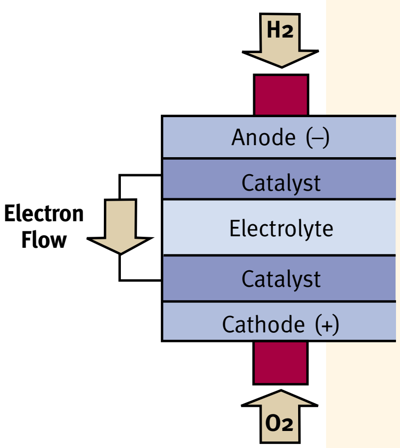
New catalysis and chemical transformations

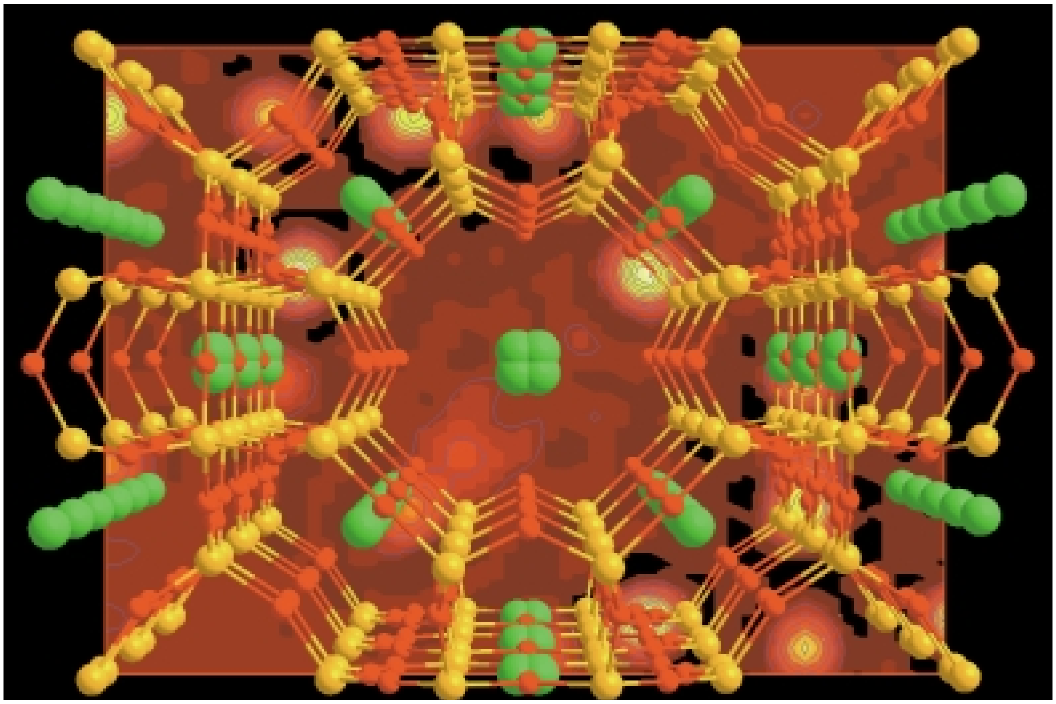
Catalysis reduces energy use in industrial processes and makes possible the manufacture of new materials by reducing the energy requirements for chemical reactions and improving desired yields. Basic research seeks to understand catalysis at the molecular level, including the roles of surface structures in reaction pathways and of carbon-hydrogen and other chemical bonds, particularly important for improving the efficiency of fuel cells.

Enzymes are biological catalysts that control metabolic processes, serving as models for low-energy, selective manufacturing processes. Engineered biosystems and scaled-up bioreactors are already used to produce products such as pharmaceuticals and synthetics and have great potential for the production of fuels and bulk and specialty chemicals. Research in biological catalysis offers the prospect of improved

Electrochemistry and Fuel Cells

A fuel cell is a static electrochemical device that converts the chemical energy of a fuel into electricity without the use of a thermal cycle (i.e., combustion) or rotating equipment. The basic components of a fuel cell are an electrolyte, an anode, and a cathode. Fuel (hydrogen) and oxidant (oxygen, typically from air) flow past the anode and cathode, respectively, generating electricity via oxidation of the fuel and reduction of the oxidant. Ions flow through the electrolyte between the anode and the cathode and through an external circuit where it can do useful work. Aside from electricity, the only by-products of these electrochemical processes are water and useful heat. Basic research in chemical and materials sciences is essential to the successful development of new fuel cells. Phosphoric acid, proton exchange membrane (solid polymer), molten carbonate, solid oxide, and alkaline fuel cells are currently a few of the fuel cell types under consideration. An improved understanding of the electrode materials, the electrolytes, and the surface chemistry at their interfaces will greatly improve the likelihood that one of these fuel cell options will become a commercially viable, and ultimately widely used, energy conversion device. Continued fundamental research in catalysis is also necessary to enable the utilization of different sources of hydrogen, including both fossil fuels and renewable sources. Developing cost effective and practical fuel cells will dramatically cut urban air pollution, reduce U.S. oil imports, and improve the energy efficiency of the whole economy.





DOE

New catalysts will be essential for advanced fuel cells. Most catalytic reactions occur on surfaces; the size and geometry of holes in a material—its porosity—is an important variable. Neutron analysis is one of the best tools for obtaining detailed structural information of the interiors of solids.

efficiency and environmental quality, with production systems operating at near ambient temperatures with low energy input, using renewable, environmentally benign feedstocks. Studies in structural biology and genomics are expected to make major contributions toward this goal and are a critical component of the Office of Science's long-term research strategy.

BY COUPLING MULTIDISCIPLINARY RESEARCH SUPPORTED BY THE OFFICE OF SCIENCE TO THE DEPARTMENT OF ENERGY'S ENERGY TECHNOLOGY PROGRAMS, THE ESSENTIAL TECHNICAL MEANS FOR SECURING ENERGY SUPPLIES WILL BE DEVELOPED. THE CUMULATIVE EFFECT OF SCIENTIFIC RESEARCH FOR NEW AND BETTER FUELS, CLEANER AND MORE EFFICIENT ELECTRIC POWER, AND ENERGY-CONSERVING APPLICATIONS WILL BE TO ENSURE A SCIENTIFIC FOUNDATION FOR ECONOMIC GROWTH, ENERGY SECURITY, AND ENVIRONMENTAL PROTECTION INTO THE NEXT MILLENNIUM.

In a hardwood forest ecosystem, a complex of instrumented towers enables researchers at Oak Ridge National Laboratory to simulate the environment of the future by releasing controlled amounts of carbon dioxide, at levels not harmful to plants, and monitoring the response.

ORNL

Protect Our Living Planet

ENERGY IMPACTS ON PEOPLE AND THE BIOSPHERE

WITH RISING WORLD ENERGY DEMAND AND MORE BY-PRODUCTS FROM ENERGY USE, SCIENCE MUST RESPOND TO THE GLOBAL CHALLENGES OF PROTECTING HUMAN HEALTH AND THE ENVIRONMENT. THE NATION'S SCIENTISTS, INVESTIGATING AREAS RANGING FROM MOLECULAR MECHANISMS OF DISEASE TO THE GLOBAL CARBON CYCLE, LAY THE FOUNDATIONS FOR LASTING SOLUTIONS.

By the 1960s, people in the United States became sufficiently aware of the burdens imposed by pollution on the economy, the environment, and human health to issue a call to action. In the following quarter century, improvements have been made in environmental quality and energy efficiency. Nevertheless, with an increasing population, the nation's total energy consumption continues to rise, even as the per-capita rate declines. More alarming still, world consumption is rising as nations increase their energy use in pursuit of economic and social development.

To meet this challenge, our society must reduce pollution, maintain healthy ecosystems, and avoid unnatural climate change, even as we clean up waste from the past. Basic research will attempt to provide a fundamental understanding of these complex phenomena, helping to inform policymakers and expand the set of viable options.

The Office of Science has identified three objectives critical to a fundamental understanding of the impacts of energy use and energy by-products on human health, in the context of broad biological and environmental effects that ultimately involve the future of the entire planet:

❶ To understand the sources and fate of energy by-products—oxides of nitrogen and sulfur, carbon compounds, heavy metals, a plethora of other agents in gaseous, liquid, particulate, or combined forms—by tracing their complex transport mechanisms and transformations through land, sea, and air.

❷ To understand how specific forms of chemical compounds act on people, other organisms, ecosystems, and the larger environment, from interactions at the level of biological molecules to long-term global effects.

❸ To combine this knowledge to create new scientific approaches that will enable us to reduce or prevent pollution in order to protect human health and the environment. Basic and far-reaching knowledge of the impact of energy use underpins all efforts to sustain the environment and to preserve the quality of human life and that of the world we live in.

Sources and Fate of Energy By-products

Objective 1: Improve our scientific understanding of the sources and fate of energy by-products

The human and environmental consequences of producing and using energy depend on where its by-products come from, how they are transformed, and where they end up. Our research programs will investigate the behavior of these by-products, on all scales from the molecular to the global.

Sources and transport in the biosphere

Greenhouse gases such as carbon dioxide and nitrous oxide, direct by-products of fuel combustion, contribute to global-scale changes in atmospheric composition. These and other by-products of energy use, such as sulfur dioxide and particulate matter, contribute to regional and local air and water pollution, creating smog and acid rain. Other energy wastes and by-products, such as petroleum residues, metals, and radioactive materials, contaminate the subsurface environment at many sites.

The reaction of carbon compounds and other greenhouse gases with plants, animals, and microorganisms—on land and in the oceans—is crucial to their abundance in the atmosphere. Basic chemical and physical investigations will track their many intricate paths through the air, soil, and water and characterize their chemical and biological transformations in molecular detail. Research has already established the key importance of human activities to the production of ozone and other oxidants in the eastern United States. Fundamental studies will seek to determine accurately the amounts of carbon, nitrogen, and sulfur spread throughout the environment in both natural and human-created forms and to determine the fates of compounds containing them.


ORNL

This "nose on a chip" developed at Oak Ridge National Laboratory is a sensor array on an integrated circuit fabricated by selectively coating microcantilever arrays with tailored chemicals. The chip, and other sensors developed by Office of Science labs, offers potentially inexpensive, instant readout with high selectivity.

Chemical interactions and transformations

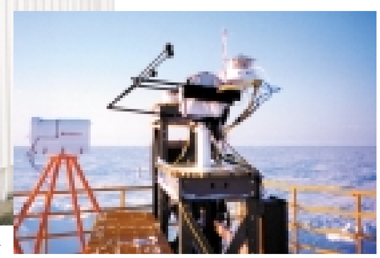
Programs in the environmental and life sciences, heavy-element and radionuclide chemistry, and molecular studies will continue to investigate how energy by-products move through and are transformed in the atmosphere and in terrestrial and aquatic environments, how they react with one another and their surroundings in different physical and chemical states, and which chemical species are taken up by microorganisms, plants, and other living things.

The carbon dioxide emitted to the atmosphere from fossil fuel combustion, for example, promptly enters the global carbon cycle. Scientific inquiry focuses on the amount of carbon dioxide that enters the terrestrial biosphere and oceans, how rapidly it is removed from the atmosphere, what controls the rate of uptake, and how long it will remain in the terrestrial biosphere.

For other by-products, also, scientists seek to understand the chemical and physical processes affecting the form and fate of energy-related pollutants released into soils and surface waters, and the meteorological processes controlling the dispersion of such chemicals and particulates in or released to the atmosphere.

Research efforts are directed toward developing and testing predictive models of these processes in the atmosphere, biosphere, and hydrosphere. Models that can take into account these complex relations will be powerful predictive tools for effective prevention, mitigation, and remediation of harmful consequences.

The Atmospheric Radiation Measurement program, coordinated by Pacific Northwest National Laboratory, collects data from all over the world to understand atmospheric properties that underlie global climate processes. Millimeter cloud radars (left) measure cloud properties directly overhead, and sun radiometers (below) aid in estimates of aerosol optical depth and the abundance of ozone and water vapor.



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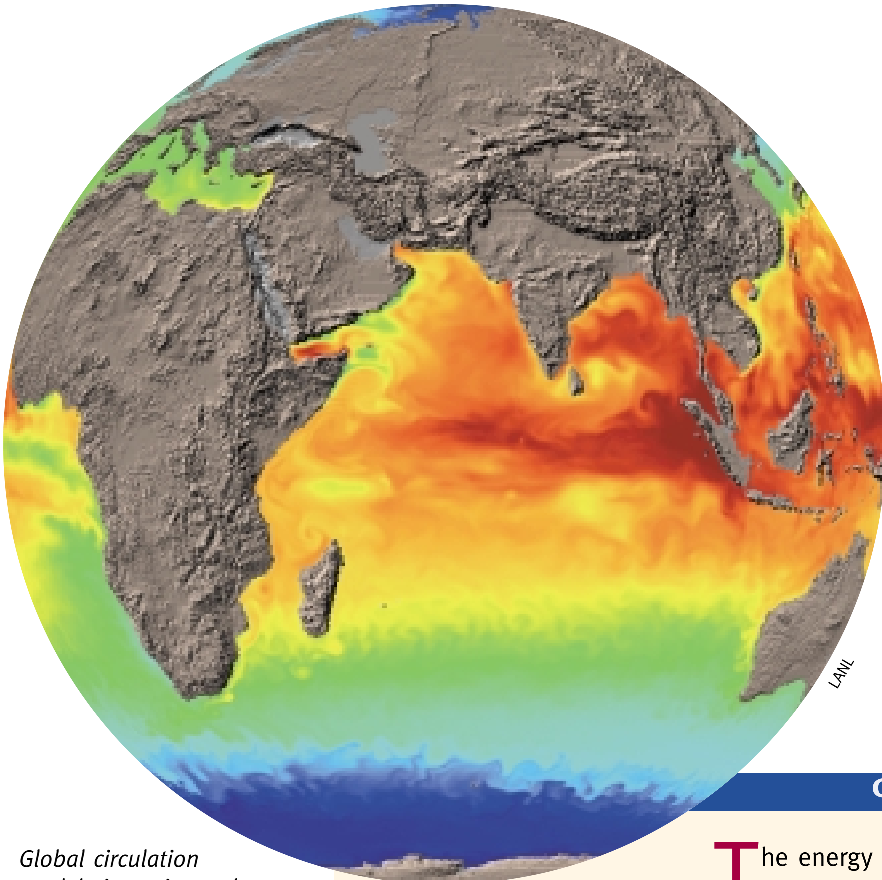


Understanding the global sulfur cycle may be important in predicting the role of sulfate aerosols on cloud formation and thus on climate. Coupled climate and chemical models may be able to explain the variation of atmospheric methane over the past century. These and similar insights will be essential guides to future energy policy, with potentially profound effects on subsequent generations.

Global circulation models investigate the role of the ocean in the climate system. Using data from surface winds and heat and salt changes in the water, the model produces moving pictures with a spatial resolution of seven to 31 kilometers in area, depending on latitude.

Climate Modeling

The energy emitted from the sun arrives in the upper atmosphere as radiation that is either transmitted, reflected, or absorbed by the atmosphere. Carbon dioxide and other greenhouse gases absorb long-wave heat radiation, so the temperature of the atmosphere and the land and sea beneath it are naturally warmer than they otherwise would be without the greenhouse gases. Over the course of decades, adding carbon dioxide to the atmosphere will lead to an enhanced greenhouse effect by trapping additional heat in the lower atmosphere, leading to increases in temperature. On the other hand, energy by-products in the form of aerosols can reflect incoming sunlight and also make clouds more reflective and longer lasting, resulting in atmospheric cooling on a much shorter timescale. Offsetting factors like these must be accounted for in any effective climate model.

The Earth's climate cycles run on numerous time scales as well. The effect of adding carbon dioxide to the atmosphere works over decades to increase temperatures, while the ocean responds slowly, over centuries, to absorb carbon dioxide—and the ocean's capacity for absorption is still not well understood.

To determine what effect energy by-products will have on global climate, extremely complex computer models account for numerous variables related to climate change, including ocean currents, changes in land use, and the variation of ice caps and sea ice. Predicting the effects on regional climate will become possible as researchers improve the resolution of models and physical modeling capabilities.

Impacts on People and the Environment

Objective 2: Provide a basic understanding of the biology and ecology of energy by-products as they affect humans and the natural world

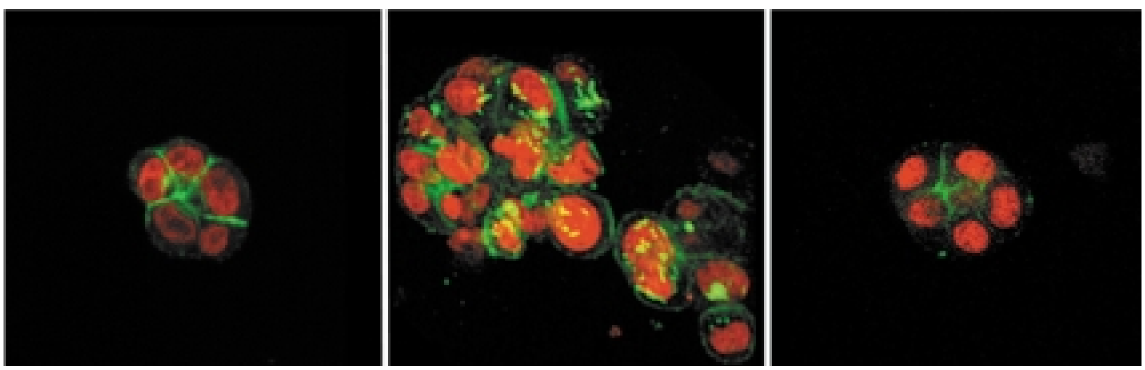
Ultimate decisions about specific methods for preventing, mitigating, and remediating unwanted effects of energy use depend first upon a detailed scientific understanding of those effects. The Department of Energy and its predecessors have been concerned with the health and environmental implications of manufacturing and using nuclear fuels and fissile materials since the earliest days of World War II's Manhattan Project; non-nuclear energy by-products are also a historic health and environmental concern. The Office of Science is a major supporter of research into the effects of energy by-products and has formulated strategies for achieving this objective, focusing on implications for human health, ecosystems, and the entire planet.

Human health impacts and risks

Protecting human health is the key concern in developing new energy technologies and in cleaning up waste and pollution. To do so—especially in view of increasing evidence that both whole organisms and individual tissues respond differently to low doses of toxic substances than to high doses—basic research is needed to help set acceptable exposure levels to chemicals and radiation.

Drawing upon new knowledge and tools developed through research into the principles of structural biology and the drive to sequence the human genome, Office of Science investigators will seek to identify the genes and gene products that control cellular responses to low doses of radiation and contamination. By determining variations in genetically based individual susceptibility to low doses, diagnostic tests can be developed to improve our understanding of potential dangers.

The response of a living organism to its environment starts at the molecular level and is propagated to cellular, tissue, and whole-organism responses. For example, researchers supported by the Office of Science have demonstrated specific molecular mechanisms by which DNA repairs itself after radiation and chemical damage—and have further shown that susceptibility



LBNL

Normal breast cells (left) appear small and regular compared to the malignant tumor cells (center) in studies at Lawrence Berkeley National Laboratory. When treated with an antibody that blocks receptors on the outer cell membrane, the malignant cells revert, as shown at right, to normal appearance and function.

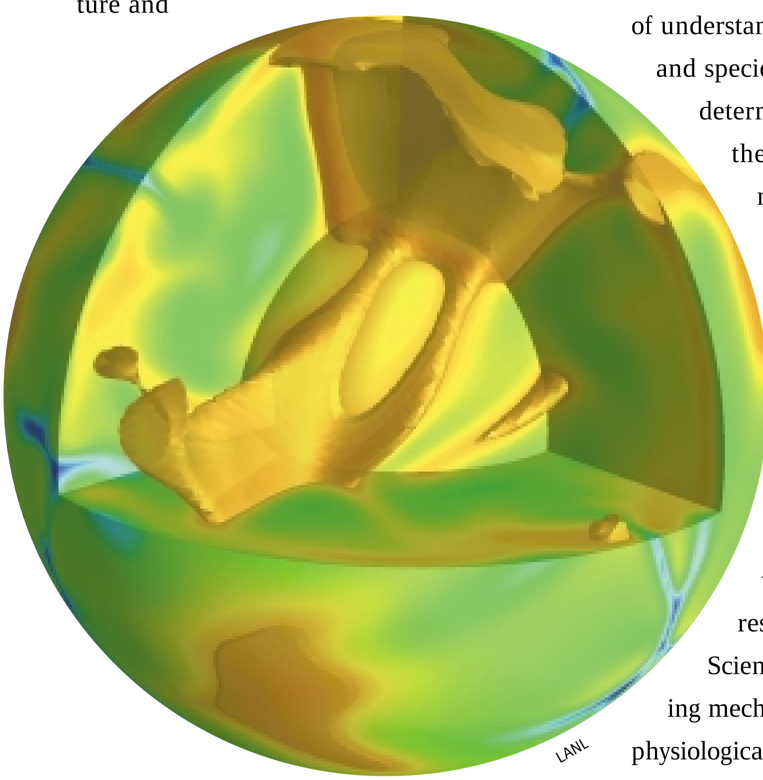
to some forms of cancer can result from genetically altered repair mechanisms. Other work has shown that miscommunication among breast cells and their extracellular matrix can lead to malignancy. Thus correct communication between the genome and the microenvironment may be key to cellular, tissue, and organism response. Changes, due to mutation and in some cases to adaptation, occur at all these levels. Unlocking these response and communication mechanisms is a strategic emphasis for future scientific studies.

Ecosystem and biological responses

In the long term, ecosystems respond to the by-products of energy-related activities according to the direct and indirect effects of the by-products on their biological structure and function. Climatic or chemical changes, such as exposure to pollutants, altered temperatures and rainfall, and elevated concentrations of atmospheric carbon dioxide, may change the rate at which energy and materials, including essential nutrients, flow through or are recycled and retained within ecosystems.

For example, terrestrial plants and microorganisms in the soil, especially in the near-surface root zone, participate in chemical cycles critical for ecosystem functioning. The responses of these organisms to exposure from chemical pollutants and temperature and moisture changes will be investigated and modeled, with the intent of understanding how individual organisms and species respond, what controls or determines their response, and how the responses can be detected and monitored.

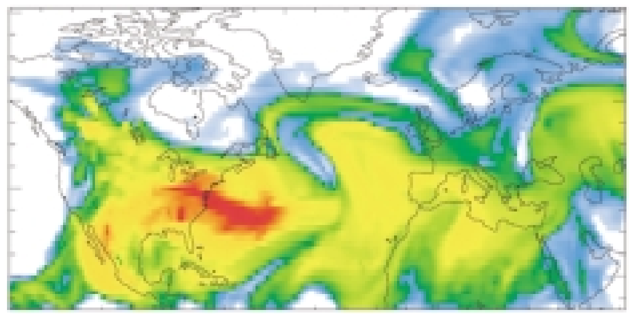
Understanding how organisms and communities of organisms respond to environmental change requires not just the ability to model responses, but to distinguish between transient and long-term ones, including adaptations. Accordingly, another research priority of the Office of Science is to investigate the underlying mechanisms, including the genetic, physiological, behavioral, and environmental



Earth's magnetic field, linked to convection patterns, rotation rates, and the chemistry of the mantle and outer and inner core, has often weakened and the wandering poles have flipped.

bases of the observed responses. This includes determining response thresholds, i.e., the level of environmental change or exposure to a stressor at which the survival or well being of organisms and communities is affected, and developing new ways of not only detecting these responses but also of identifying their specific causes.

Only through such scientific investigation of the functioning of ecosystems and of their levels of tolerance can we ensure their sustainability in the face of such natural and artificial changes as global warming and cooling.



BNL

Scientists at Brookhaven National Laboratory model anthropogenic sulfate aerosol emissions to understand their potential to increase atmospheric reflectance and modify global radiative heat balance.

Regional and global consequences

Understanding the long-term effects of energy use will depend upon suites of sophisticated computer models of the entire global system that take into account interdependent physical, chemical, and biological processes over decades and centuries. To do so, Office of Science researchers will construct improved computational models—based upon comprehensive, high-quality geophysical data—that have the necessary fine-scale representations of such linkages as that between cloud and sun and ocean and atmosphere.

These fine-grained models will then be tested to determine their sensitivity to a range of initial conditions and variables and to localize the analyses. For instance, the effect of different greenhouse-gas emission scenarios on climate-change forecasts will be tested, as will how different regions of the world might respond to a changing climate. The ultimate objective? To furnish policymakers with predictive models of sufficient detail and reliability to develop local, regional, and national policies and plans with confidence.

OBJECTIVE 3: CREATE NEW SCIENCE-BASED APPROACHES TO MINIMIZE ENERGY BY-PRODUCTS AND PROTECT THE BIOSPHERE AND HUMAN HEALTH

Even the most efficient use of energy unavoidably involves by-products. Some are serious pollutants and contaminants, requiring advanced scientific methods of neutralization, sequestration, re-use, or when necessary mitigation. We will help minimize these by-products and mitigate their effects on the environment and health through basic research to minimize pollution, clean up contaminants, sequester carbon, and improve both medical treatment and the scientific basis of health regulation.

Pollution minimization

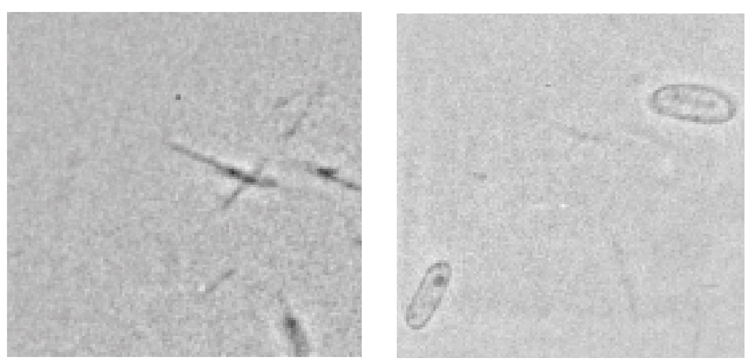
Office of Science programs seek the scientific bases for advanced means of minimizing, separating, disposing of, and converting pollution caused by industrial operations and the combustion of fossil fuels. Research will target a broad range of sciences, including investigations on molecular interactions at surfaces and membranes, ion exchange and transport, catalysis, and active media for selective adsorption of pollutant species.

In addition to these combustion and industrial-process studies aimed at minimizing pollution, genetic and structural biological researchers will study the potential of microorganisms to offer ready-made solutions to such challenges as efficient energy production, environmental cleanup, and minimal emission of atmospheric carbon. It is already known, for example, that some sulfur-removing microbes can render gasoline clean-burning.

Cleanup and remediation

While the Office of Science is actively pursuing research to prevent the generation of new wastes, DOE is faced with the legacy of wastes from nuclear weapons manufacture during the Cold War. Both cleanup of heavy metals, radionuclides, chlorinated solvents, and other wastes, and safe long-term storage of nuclear wastes, are the targets of basic science programs. Research is needed to provide a detailed understanding of the chemical interactions of energy by-products, their fate in the environment, and the potential for transforming wastes into more benign forms.

Geologists will study how pollutants are transported through geologic media under different thermal, chemical, mechanical,



University of Wisconsin-Milwaukee/DOE

X-ray images taken in the same area of a water sample at different wavelengths show needle-shaped particles of manganite and the bacteria which have ingested them. This University of Wisconsin-national laboratory collaboration indicates how bacteria could be key agents in removing metals and other contaminants from soil and water.

and hydrologic conditions; improvements in high-resolution, three-dimensional geophysical imaging will help track waste plumes under the surface. Chemists will devise imprinted polymers to seek out specific metal ions. Materials scientists will study glasses and ceramics for encapsulating radioactive substances. Molecular environmental scientists will distinguish among chemical species of contaminants on the basis of their stability, toxicity, mobility in the soil and water, and availability for take-up by living things; chemical species resistant to traditional cleanup methods will be identified.

Bioremediation uses microorganisms to remove hazardous contaminants by transforming them into benign substances or sequestering them in place. Versatility, ease of use, and low cost in cleaning up contaminated sites are among the potential benefits of bioremediation research. Several naturally occurring microorganisms have been identified with such useful properties as extraordinary resistance to radiation, the ability to degrade solvents, or the ability to remove or immobilize metals. By moving genes for solvent degradation into a radiation-resistant microorganism, the modified microbe could be able to survive in high-radiation environments and clean up toxic waste. Basic research will address whether more versatile and rugged microorganisms can be identified in nature or genetically modified in the laboratory for the toughest cleanup jobs.

Research on accelerator transmutation, a technique to alter the elemental composition and radioactive properties of materials, may result in a means to treat radioactive waste that greatly reduces storage time and recovers substantial amounts of energy.

Metal-Reducing Bacteria

Some species of naturally occurring bacteria can add electrons to metals such as uranium or chromium, causing them to precipitate out of solution. The removal of metals and radionuclides from contaminated groundwater, for example, reduces the potential risk posed to humans and their environment. Contaminants such as plutonium, uranium, and chromium could be immobilized as solids by bacteria. Another means of cleaning up metals is to digest and mineralize them by binding with hydrous oxides, which react with contaminants and fix them on the surfaces of mineral deposits. Investigations are under way to learn how these and other natural processes might be harnessed and accelerated for bioremediation.

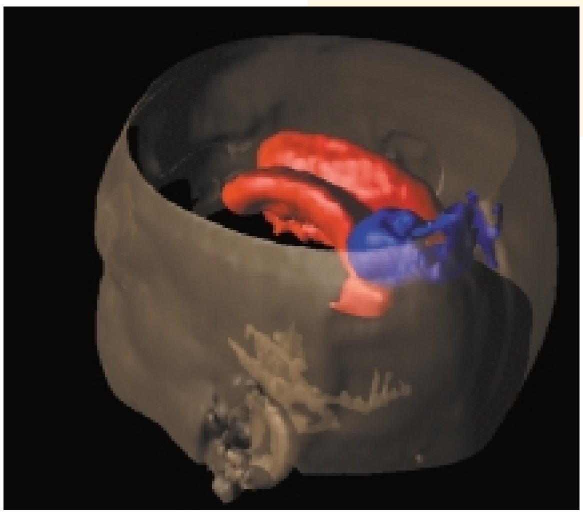
Carbon sequestration

Energy by-products and nuclear waste are well known problems, but one of the most pressing for protecting the earth's climate is that of carbon sequestration, which has given rise to the new science of carbon management. A major research objective of the Office of Science is to understand how the natural carbon cycle is affected by energy use. To place the problem in perspective, in the United States fossil fuels account for almost nine-tenths of the energy consumed, with carbon dioxide as the major by-product. Worldwide, six billion tons of carbon dioxide are released into the atmosphere every year.

Enhancing natural mechanisms of carbon sequestration by terrestrial and ocean biota could significantly slow the rise of atmospheric carbon dioxide. Science-based carbon management to increase sequestra-

Boron Neutron Capture Therapy

Tumors impossible to remove surgically, such as the brain cancer glioblastoma multiforma, a highly malignant brain cancer, may be treated safely with a new form of radiation therapy called boron neutron capture therapy (BNCT). Patients are injected with a boron-containing chemical that accumulates in tumorous, but not healthy, tissue. The tumor is then irradiated with a stream of neutrons generated from a nuclear reactor or a particle accelerator. The neutrons interact with the boron and generate highly energetic charged particles that travel through the tumor but do not reach the normal cells, thus limiting the side effects of the treatment. Ongoing clinical trials have verified the safety of the procedure, and others are being planned to compare the effectiveness of BNCT to that of standard treatments for incurable cancers.



INEEL/BNL

Boron neutron capture therapy requires three-dimensional information about a patient's tumor. Medical imaging data, anatomical models generated by computer, and radiation transport calculations help determine the treatment plan. The biophysical model shown was developed at Brookhaven National Laboratory in conjunction with the Idaho National Engineering and Environmental Laboratory.

tion is also expected to create new products and energy sources and could enhance the environment in other ways. For example, sequestered carbon could prove a valuable commodity that enables the extended use of fossil energy while transitional energy sources are developed.

The knowledge of how much and how fast carbon dioxide is incorporated by forest, grassland, and ocean organisms will suggest which processes, rates, and quantities offer the best opportunities for modification to enhance the natural sequestration of carbon in terrestrial and oceanic environments.

Research to devise cheaper and more efficient ways to separate the carbon-rich from hydrogen-rich components of fuel feedstocks is also needed. Scientists will analyze newly discovered microorganisms and develop new high-temperature techniques for thermal decomposition to provide the basis for decarbonizing fuels with new catalysts, enzymes, and biological methods.

Discovering more effective ways to separate carbon dioxide from flue gases and the atmosphere is another research priority. These include new solvents for use in corrosion-resistant distillation at very high or very low temperatures; new membranes, catalysts, and molecular sieves for removing carbon dioxide; and enzymes and organisms, including genetically modified microorganisms and plants, for fixing carbon dioxide.

Research will also explore new ways of sequestering carbon dioxide, including storage in subsurface rock formations such as salt domes and coal seams, in depleted oil and gas reservoirs, or in the ocean.

Health protection and medical research

Accurate predictive models of the behavior of energy by-products in the biosphere, from the immediate and instant to the global and long-term, will help establish acceptable exposure levels and place strategies to protect human health on firm scientific foundations.

New technologies, derived from energy research and developed through Office of Science programs, already promise advanced methods of diagnosis and treatment to address a wide range of human health problems.

New synthetic organic chemistry techniques will allow the rapid radiolabeling of biological molecules to target metabolic pathways, enzymes, ribonucleic acids, and the immune system—information that will be used to develop new drugs. Heart and brain disorders, neurodegenerative diseases, and cancer are the targets for diagnosis and treatment using radiopharmaceuticals.

Advanced computational methods and new imaging technologies using lasers, positron emission tomography, magnetic resonance imaging, and magneto-encephalography for probing tiny magnetic fields in the brain will result in new tracer methods for molecular biology, better ways to measure vital organ function, and improved monitoring of chemotherapy, radiotherapy, and gene therapy.

Novel boron compounds and tissue-penetrating neutron beam facilities will be developed and clinical trials conducted to evaluate the promise of boron neutron capture therapy for cancer.

What are the molecular- and cellular-based mechanisms for protecting human health and the biosphere? How do energy production and use alter the composition of atmospheric gases and change the world's climate? What is the safest, longest-lasting way to prevent air, water, and soil contamination from nuclear waste and other energy by-products? These and a host of other questions will be answered as researchers at universities, national laboratories, and private industry—supported by the Office of Science and using its extraordinary tools—learn to quantify, predict, and mitigate the effects of energy use. Future deliberations can then be grounded in improved understanding and sound science.

The most distant and ancient galaxies visible from Earth in this representative slice of the night sky—along with everything else in the universe—sprang from the fundamental particles and forces of the Big Bang. The radiative and dynamic properties of the ancient galaxies, their stars and supernovae, provide insights to the origin and fate of the cosmos—and of matter and energy.

Hubble Deep Field Team/NASA

Explore Matter and Energy

BUILDING BLOCKS FROM ATOMS TO LIFE

DURING THE 20TH CENTURY, WE LEARNED THAT MASS AND ENERGY ARE EQUIVALENT, THAT THE UNIVERSE BEGAN WITH A HOT BANG AND MAY END IN A CHILL, AND THAT DNA CODES PROTEIN STRUCTURE. INDEED, GREAT SCIENTIFIC ADVANCES COME FROM THE EXPLORATION OF THE SMALLEST COMPONENTS OF LARGER STRUCTURES AND PHENOMENA. UNDERSTANDING MATTER AND ENERGY—IN ALL ITS FORMS—HAS CHANGED OUR LIVES IMMEASURABLY AND ALTERED THE WAY THAT WE VIEW OUR WORLD AND OUR UNIVERSE. OUR NATION'S SCIENTISTS ARE POISED TO DELVE EVEN DEEPER INTO THE BUILDING BLOCKS OF MATTER AND OF LIFE ITSELF.

One of the great quests for scientists over the past centuries has been to understand and ultimately control nature. Exploring matter at deeper and deeper levels has resulted in knowledge spanning scales from the molecular, to the atomic, and ultimately, to the subatomic and beyond. Now, experiments in particle, nuclear, and astrophysics are providing glimpses into a more complete understanding of what the world is really made of and how it works. On a larger scale, the constituents of matter and energy are assembled in complex molecular structures, and are organized in the biosphere into the fabric of life. Understanding these complex relationships gives us a considerable advantage in adapting them for effective use.

The Office of Science has identified three objectives as critical fields for future exploration in understanding the building blocks of all matter and life:

1. To apply fundamental physical theories to understand the most basic components of matter, the elementary particles and the forces through which they interact
2. To understand the origin and fate of the universe, and the evolution of life, through basic physical theories
3. To understand and learn to control the ways these simple building blocks can be assembled, or can assemble themselves, into complex systems of great versatility and usefulness

Components of Matter

Objective 1: Understand the nature of matter at the most fundamental level

To a high-energy physicist, quarks are building blocks, which may combine in nucleons—complex objects with structure. To a chemist, a nucleon is itself a building block, a basic unit of mass, charge, and spin, which can form complex systems of atoms and molecules. To a biologist, even giant molecules are building blocks, the constituents of cells and complex organisms. The Office of Science leads the world in supporting the study of these fundamental building blocks of the universe; our strategy for understanding better the nature of matter is to focus on: elementary subatomic particles, nuclear matter, atoms and molecules, and biomolecular building blocks.

Elementary particles and their interactions

Understanding the most fundamental particles of matter and the forces acting on them is the challenge and the realm of high-energy physics. The Standard Model of Fundamental Particles and Interactions, a landmark theory, has explained many of the most fundamental aspects of matter. The predictions of the model agree remarkably well with experiments over a very large range of energies, and it accounts for a

Quark and Lepton Flavors

Quarks come in six different flavors, with the familiar, every-day matter being made up principally of the up and down varieties, while the charm, strange, top and bottom quarks are more massive and unstable. The up and down quarks can only be produced at particle accelerators and colliders, or by astrophysical sources.

The second class of particles is comprised of leptons, the best known of which is the electron. Two additional charge leptons, the muon and the tau, have the same electrical charge as the electron but much greater mass, and are unstable. The other three leptons are the very elusive neutrinos, which have no electric charge and very little, if any, mass.

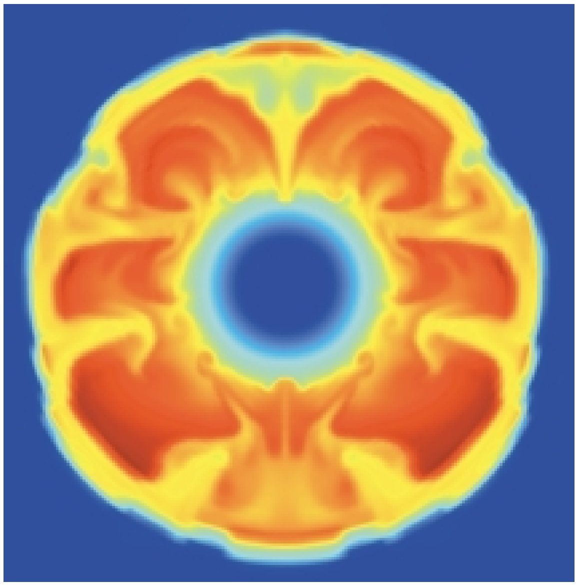
The Standard Model attempts to explain some of the fundamental forces affecting quarks and leptons and their interactions. The forces come in four basic types: gravitational, electromagnetic, strong, and weak. These fundamental forces explain, among other things, how atoms are held together and why certain nuclei decay. Current theory explains that these forces arise because of the exchange of other fundamental particles, called bosons, much like the familiar photon, the carrier to electromagnetic force. The measurement of bosons at accelerators such as Stanford Linear Accelerator has confirmed the nature of the weak force.

broad range of subatomic particles, including the various forms of quarks and leptons.

Against this backdrop of accomplishment and optimism, there have been recent discoveries that pose extreme inconsistencies and, to an extent, challenge some of the very fundamental tenets of the model. Whether the Standard Model can prevail or not, only time will tell, but these discrepancies are not so easily explained away, and some scientists are beginning to challenge the model itself and to consider alternative explanations. One such proposal is superstring theory, based on the premise that matter is not a collection of points in space, but a series of strings. Other theories are also emerging. Regardless of the outcome, priority will be placed on experimental and theoretical research that can shed light on these anomalies and related phenomena.

For example, research will attempt to address why the model is unable to explain adequately the observation that there are three families of quarks and leptons, no more and no less, and why the charge of the proton, built from quarks, so perfectly equals the charge on the electron, which is not built from quarks. Research must answer why quarks and leptons have the masses they do, how they acquire the property of mass and the apparent lack of pattern to their masses, and why the W and Z bosons are so heavy, yet the photon and gluon have zero mass.

On a more general level, the Standard Model cannot adequately explain why the universe is seemingly dominated by matter, rather than possessing a symmetry between matter and antimatter, as might be expected from a starting point of pure energy, the Big Bang. And the Standard Model also says that neutrinos do not have mass, but experimental results in 1998 provided the first firm evidence that neutrinos oscillate from one kind of neutrino to another, which is only possible if neutrinos have mass. This, too, will be a focus for future research.



Dr Anthony Mezzacappa, ORNL

The nuclei of all elements heavier than iron were formed in the explosions of supernovas. These simulations, conducted by Oak Ridge National Laboratory and the University of Tennessee, show the entropy in neutrino transport and convection during core collapse.

Overall, future scientific inquiry will be designed to help clarify whether the Standard Model remains valid or whether it is time to move beyond this theory to one that provides a clearer explanation of observed phenomena. The scientists and resources applied to this quest will explore the very essence of existence, and many in the field believe that they may be close to realizing a new wave of revolutionary breakthroughs in understanding.

Nuclear matter and interactions

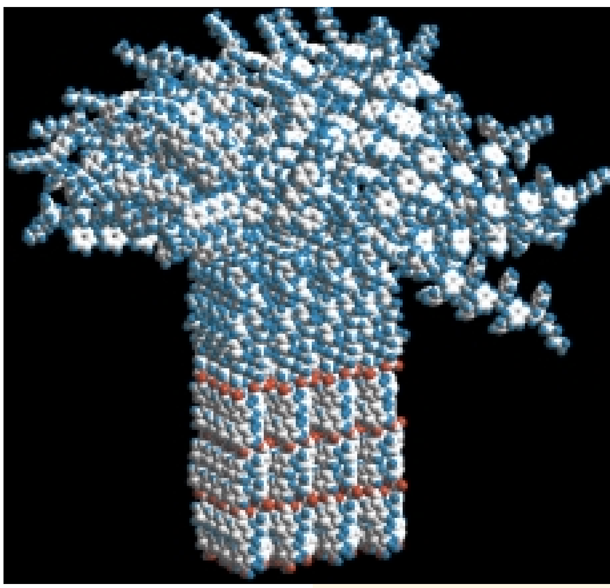
Current scientific understanding is that everything needed to build atomic nuclei condensed out of a quark-gluon plasma within a ten-thousandth of a second after the Big Bang. Yet all nuclei heavier than lithium were formed much later in the hearts of stars or, for those elements heavier than iron, fused in the titanic shock of exploding stars.

Aspects of the formation, structure, properties, and interactions of nuclei predicted by the Standard Model will continue to be the subjects of intense scientific investigation. Nuclear scientists are pursuing research in four broad areas of exploration: the limits of nuclear structure and dynamics; the quark structure of matter; the phases of nuclear matter; and the theoretical studies of fundamental symmetries and nuclear astrophysics.

Nuclear physicists will attempt to understand, for example, the creation of the elements by nucleosynthesis in stars, the remarkable new behaviors of protons and neutrons in very rapidly spinning nuclei, and the recent, surprising finding that different nuclei can have identical gamma ray emission patterns.

Physicists will continue to explore the inner structure of a single proton or a neutron, where quarks and gluons are confined in very complex ways.

Just as water changes to steam, so nuclear matter can change phases with a change of conditions. Researchers using



Dr Samuel I. Stupp/University of Illinois at Champaign-Urbana

A "rodcoil" forms from individual polymers with both rigid and flexible ends. In one formulation conducted at the University of Illinois at Champaign-Urbana, the rods are capped with slippery chemical groups and the coils with sticky groups; the units assemble themselves into thin films, with one surface more tenacious than paint and the other slipperier than grease.

Rodcoils

Rodcoils are an elegant example of a new class of self-assembling materials resulting from fundamental research sponsored by the Office of Science. A group of utterly unexpected yet useful new materials assembles its own nanostructural building blocks from miniature polymers. Dubbed "rodcoils," the polymers possess rigid, rod-like bases and flexible, coil-like tops. The rods stick together like a bundle of pencils, while the coils repel one another like a head of wild hair. When a hundred or so of the rodcoils have coalesced, their attractive and repulsive forces balance, leaving a mushroom-shaped nanostructure.

These "mushrooms" in turn bundle themselves side by side in polar alignment, stacking themselves a hundred layers deep in thin films which can be engineered with a variety of electrical, optical, mechanical, and biological properties.

The films are sticky on one surface and slippery on the other, like invisibly thin adhesive tape. With two different surfaces, such films could be used to repair blood vessels or to coat concrete and metal with a moisture barrier that adheres more effectively than paint, to reduce corrosion in bridges and other structures, and to act as long-lasting aircraft wing de-icers.

collisions of heavy ions are beginning to explore what appears to be the quantum-systems analog of a liquid-gas phase transition, and, at even higher energy densities, the transition from hot, dense nuclear matter to a quark-gluon plasma.

And finally, nuclear physics experiments will make precise measurements at low and intermediate energies, continuing to play an essential role in exploring the limits of the Standard Model. The role of the nuclear physicist will complement that of the high-energy physicist, the latter working at the highest energies—and hence smallest scales—possible.

Atoms and molecules

Whether hard as diamond, smooth as oil, or friable as chalk, surfaces only hint at the intricacies within materials, where a frenetic dance of matter and energy determines both fundamental and transient properties.

Studying atoms and molecules as building blocks reveals numerous insights: into the nature of combustion, the properties of thin films, the dynamics of the liquid-gas interface, and movements in atomic clusters, to name a few.

Researchers in this area will continue to study the phenomenon of superconductivity, for example, investigating how high-temperature superconductivity arises in metal oxides. They will attempt to unravel the secrets of "giant magnetoresistance," in which the electrical resistance of a material drops dramatically when a magnetic field is applied. And they will scrutinize the ways in which magnetic properties and conducting or insulating properties change with pressure and temperature.

Biomolecular building blocks

Genetic information specifies chains of amino-acid residues that fold into elegant three-dimensional protein structures, crucial to their function in cells and tissues. Among other intricate questions concerning the translation of information into life's functions, sequencing the genomes of human beings and other organisms and solving the problem of protein forward folding and the relationship of the resulting structure and biological function are two of biology's important pursuits.

To sequence fully and rapidly the human genome, new technologies and new computer-based tools will be applied to identify the functional units, and suites of units, in a cumulative sequence that is three billion base-pairs long.

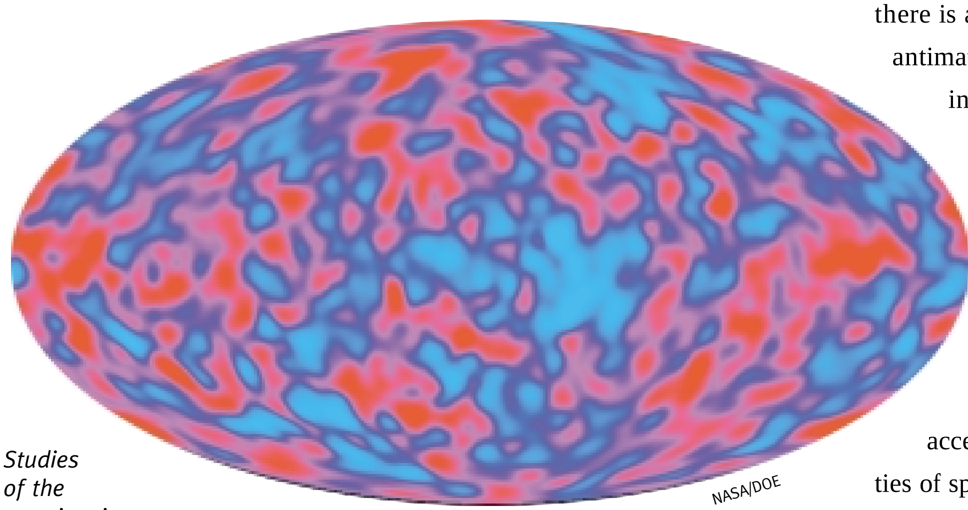
Before we can fully understand how proteins work, we must solve their structures—an estimated 100,000 of them specified by the human genome. Experiment discovers protein structures directly; theorists seek underlying laws by which a string of amino-acid residues folds into a unique structure.

The interactions of structural, operational, and regulatory proteins depend not only on their shapes and atomic structures but also on the chemical and physical conditions of the organism. New experimental and computational tools, bringing together a variety of disciplines, will be applied to the study of the manifold processes of cells and tissues.

Armed with intimate knowledge of how biomolecules work, we will be able to modify, even perhaps create, entirely original enzymes and other proteins for applications in medicine, industry, and energy.

OBJECTIVE 2: EXPLORE THE EVOLUTION AND FATE OF THE UNIVERSE THROUGH THE FUNDAMENTAL INTERACTIONS OF ENERGY, MATTER, TIME, AND SPACE

These are exciting times for the study of the universe: there is strong evidence for the Big Bang as the origin of the universe; the existence of predicted black holes has been confirmed; astrophysical phenomena explain the origin of matter; and strong evidence now exists for gravitational waves, one of the predictions of general relativity. Yet we would understand none of these astrophysical phenomena today if it were not for our understandings of matter and energy at the smallest scales from experiments on earth.



Studies of the cosmic microwave background radiation supported by DOE and NASA produced this sky-map of the relic radiation of the Big Bang. Small anisotropies in the energy density of the young universe have been magnified by gravity, causing matter to cluster into galaxies and larger structures.

Beginning of the cosmos

In recent years the scientific research of particle physicists, who study the smallest specks of matter, and that conducted by astrophysicists and cosmologists, who study matter's largest manifestations, have become increasingly connected. Indeed, theorists who seek a more fundamental explanation of particles and their interactions must now ask if their theory predicts a unique universe—and if so, is it the one we live in? Theories must consider why there is a preponderance of matter over antimatter in the universe, and the role of invisible dark matter in the origins and fate of the universe.

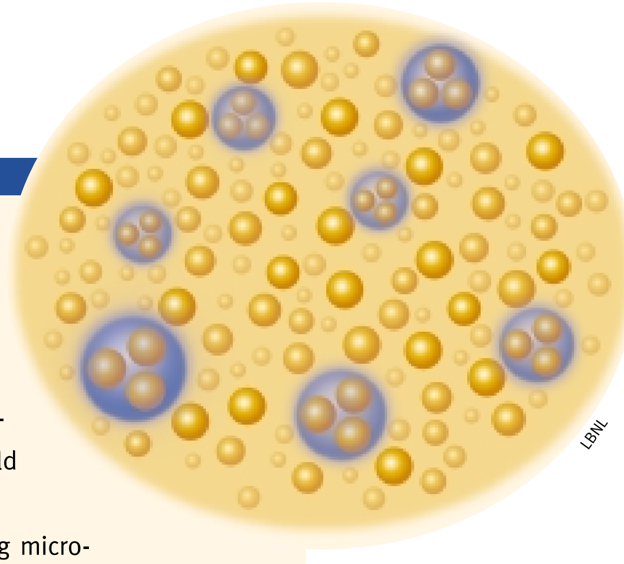
Perhaps one of the more intriguing questions, prompted by recent DOE-sponsored evidence that the universe is expanding at an *accelerating rate*, centers on the basis for this acceleration and the unusual properties of space that would give rise to this observation.

Creation of nuclei and matter

How the lightest atomic nuclei came into being is the story of the first three minutes after the Big Bang; in a contrasting story, heavier elements were created much later by the death of giant stars. Astronomical observations and high-energy physics experiments cooperate to tell the tales.

Chapters in the stories include the formation of atoms, the production and propagation of neutrinos, the nature of cosmic rays, the persistence of matter, the sequence of stellar burnout and collapse, and the mechanisms of supernovas.

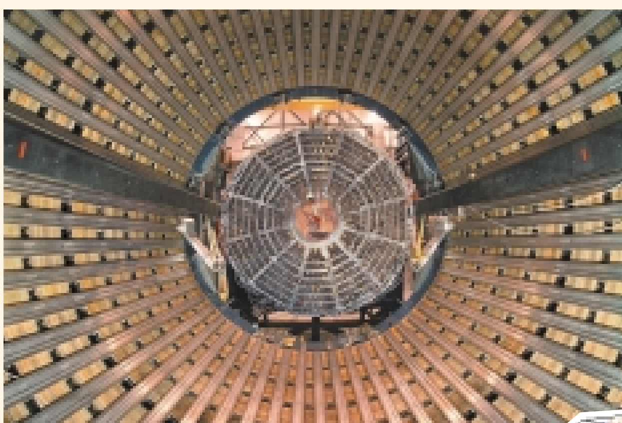
Quark Matter


LBNL

In the Standard Model of particles and interactions, quarks are the fundamental constituents of matter, and gluons are the carriers of the strong nuclear force that binds quarks into protons, neutrons, and other particles. But for a few instants after the Big Bang, the heat and density of the universe were so great that gluons could not hold quarks together.

Office of Science physicists hope to recreate the Big Bang microscopically by colliding beams of nuclei together at very high energies; if they look quickly—the whole thing is over in a billionth of a trillionth of a second—they may see free quarks for the first time.

Quark matter may not be rare, however. The universe is littered with pulsars, cinders of supernovas so dense that their very atoms have been crushed, and their protons and electrons have interacted to form neutrons. As long as the pulsar spins fast enough, no further collapse is possible.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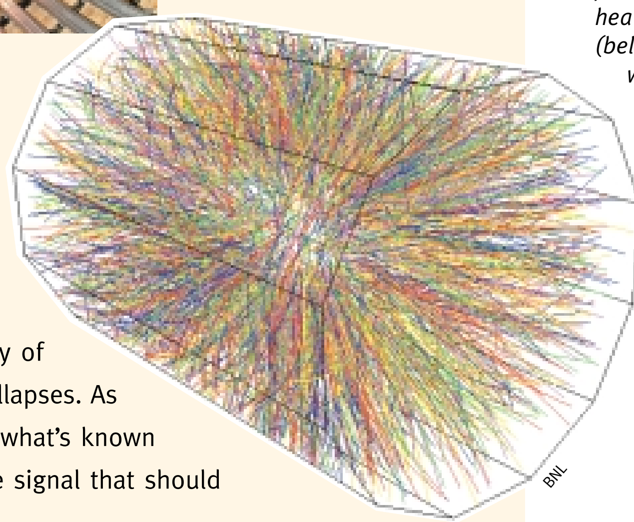
But as the pulsar's rotation inevitably slows, gravitational pressure is no longer offset by centrifugal effects and neutrons are released, thereby freeing their quarks.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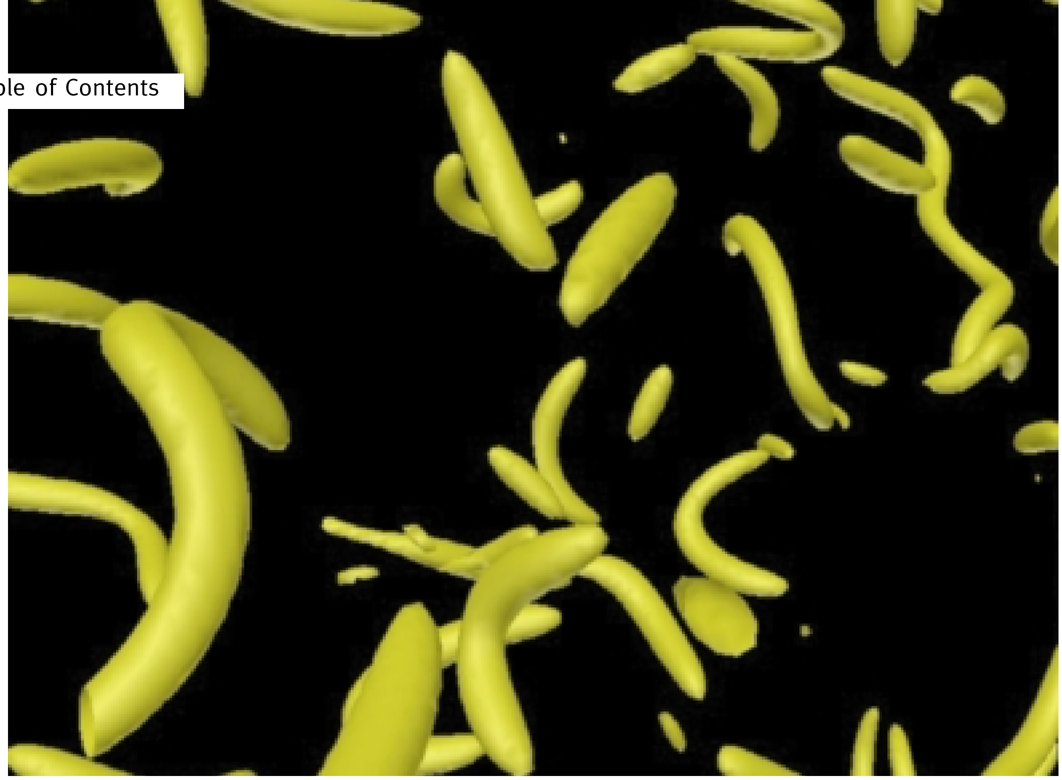
Theorists believe that quark matter, which is believed to have the consistency of soup, condenses as the spinning star collapses. As the star shrinks, it spins faster, emitting what's known as a "signal of deconfinement," a unique signal that should be unmistakable to a radiotelescope.

Of the 700 known pulsars in the universe, as many as seven may be undergoing this process right now and possibly emitting this signal. A radiotelescope picking up this signal of deconfinement would be a major discovery, one that would support and help validate both the Standard Model of physics and the notion that the early universe was made of a hot quark soup.

Astrophysicists search the sky for traces of free quarks in the cores of spinning neutron stars. Researchers using the STAR Detector at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory will seek direct evidence of free quarks (above). The jets of matter tracked through the volume of the Time Projection Chamber (left) inside STAR will offer evidence for a quark-gluon plasma produced from the heavy-ion collisions (below). This plasma, with its free quarks, filled the universe in the first moment after the Big Bang.



Theoreticians investigate strange objects called semilocal strings, which may have condensed out of interacting quantum fields a hundred billionth of a trillionth of a trillionth of a second after the Big Bang, triggering the dominance of matter over antimatter and strewing the seeds of galactic structure.

Scientists will seek to understand how quarks joined to form protons, neutrons, and heavier baryons, how protons and neutrons joined to form bare nuclei, and the role of neutrinos in this process. They will investigate the relative amounts of nuclei in the universe, the process by which stars and other astrophysical mechanisms produce and propagate neutrinos, and the production of cosmic rays as well as their modification as they traverse the interstellar medium. Finally, scientists will seek to solve the mysteries of stellar burnout and collapse and supernovas, exploring how matter changes in spectacular ways.

Evolution of astrophysical structures

How stars and galaxies formed depends, in part, on how “smooth” the early universe was. Tiny imperfections, still detectable as anisotropies in the cosmic background radiation amounting to only a few parts per million, were the seeds of what are now immense configurations of matter. How did the universe expand after the Big Bang? What role do vast filamentary networks of plasmas play in the larger structure of the universe?

Researchers seek to determine the role of elementary particles in stellar evolution—including the death of massive stars in black holes—as well as the formation of galaxies, the production of more stars, and the evolution of mature galactic shapes. Stars may have formed in a clumpy medium of hydrogen and helium, or from shock waves propagated in smooth gas by supernovas, cosmic strings, or by some other astrophysical mechanism. General relativity and quantum theory, yet to be united, are both essential to a full understanding of these and many other phenomena.

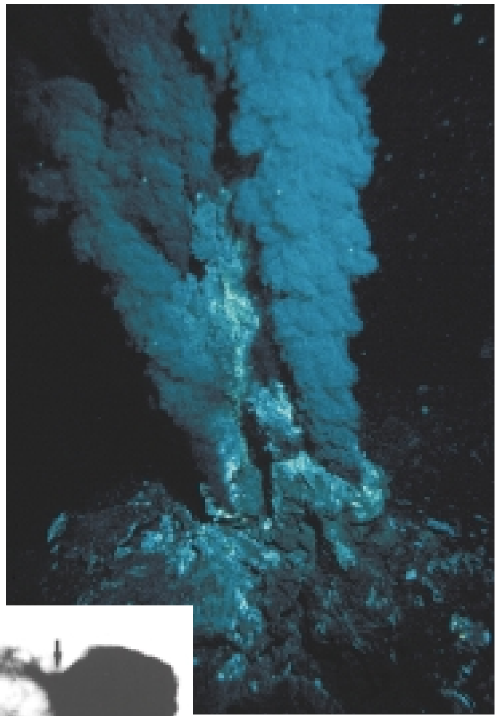
Formation of life

Related genes and their products, elaborately assembled in subcellular structures, are shared by creatures from the simplest to the most elaborate. Even a simple invertebrate, such as a roundworm with a few hundred cells in its nervous system, possesses genes for most of the molecular components found in vertebrate brains.

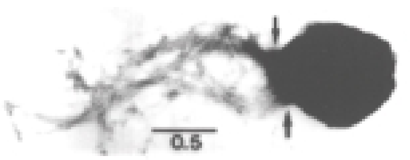
Simple and complex genomes are compared to identify relationships and likely ancestries. Researchers study conserved subcellular entities such as ribosomes and mitochondria to understand the origin and evolution of these building blocks of all life.

Office of Science investigators seek out and analyze organisms living in extreme conditions and search for undiscovered strains of wild microorganisms to determine the phylogenetic relationships among their communities. In this way researchers have discovered an entirely new kingdom of life, the Archaea, and have sequenced the genome of one such organism, a methane-producer living in "white smoker" vents on the deep ocean floor.

The properties of such primitive microorganisms may prove useful for bioremediation, as well as industrial, medical, and agricultural applications. Scientists may develop the capability to design novel proteins, specialized tissues, and even whole organisms from a few basic evolutionary units.



Woods Hole Oceanographic Institution

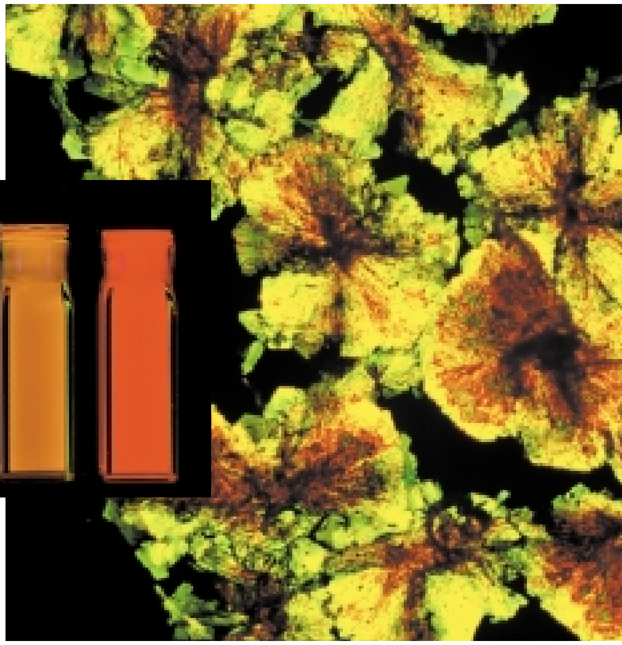


National Center for Genome Resources

In the darkness surrounding deep ocean vents lurk Archaeons, the most ancient forms of life. Researchers at The Institute of Genomics recently sequenced the first complete genome of a member of this third kingdom of living things, Methanococcus jannaschii*—a heat-tolerant, metal-binding methane producer with possible uses in fuel, chemical, and pharmaceutical production and toxic waste clean-up.*

OBJECTIVE 3: CONTROL COMPLEX SYSTEMS OF MATTER, ENERGY AND LIFE

Experimentation, design, and computer simulation are needed to understand and control complex structures—from molecular systems of materials to living organisms. How can we harness and control the exquisite complexity of nature? How can we design materials, from their fundamental atomic and molecular building blocks, with predictable tailor-made properties? Nature's achievements serve as benchmarks for the ultimate control of systems that will be important to the technology of the 21st century. Our strategies for understanding and controlling such systems include the investigation of complex phenomena and adaptive systems.



Semiconducting nanocrystallites, large enough to have crystalline cores but too small to exhibit solid-state band structures, have numerous technical applications. The optical and other properties of chemically identical cadmium-selenide "quantum dots" depend only on their size, as shown by the range of colors in these vials from work conducted at the Massachusetts Institute of Technology.

Complex phenomena

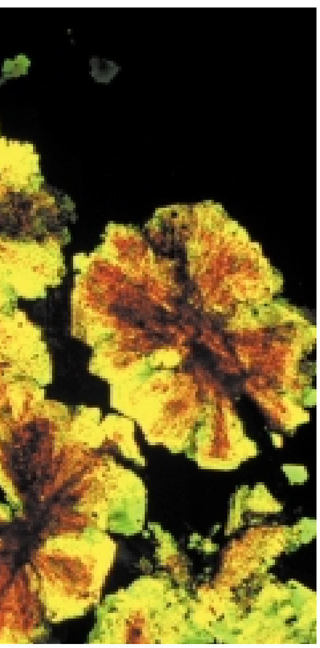
Atomic structures may evolve into complex molecular structures, such as those found in ceramic superconductors, metallic glasses, and biomolecular materials. If we understand the most efficient pathways of evolution, we may be able to control the architectures of molecules and nanomaterials to tailor their optical, electrical, and magnetic properties.

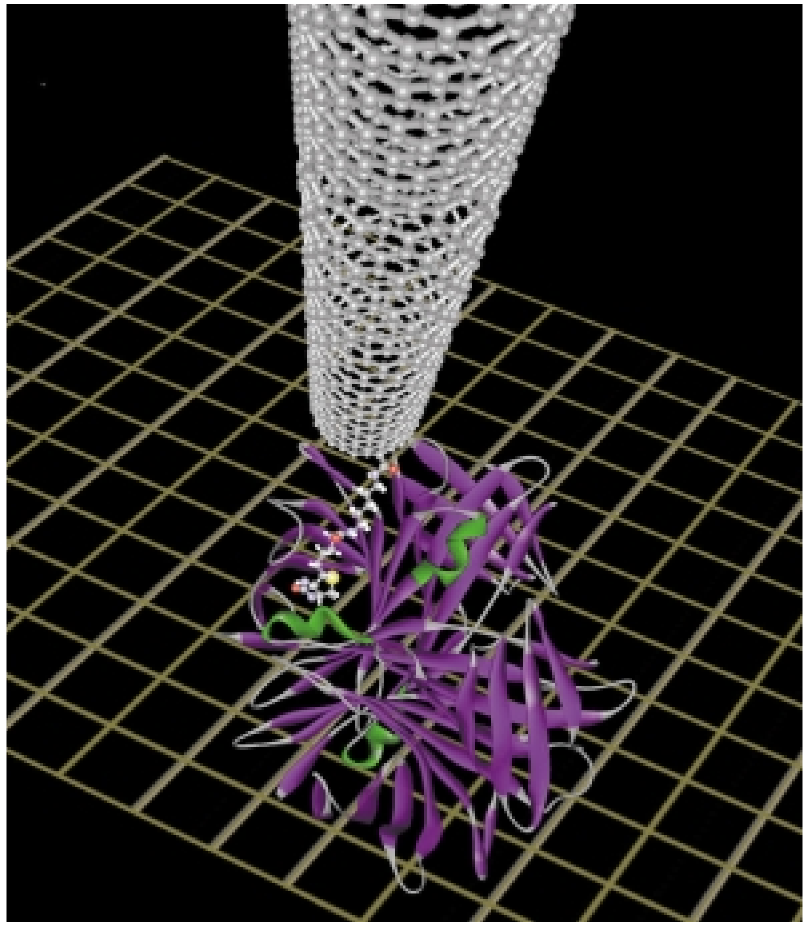
Office of Science investigators seek to identify the organizational principles of complex fluids and polymers, aiming to control molecular organization, materials synthesis, and growth in thin films and other metastable systems. Superconductivity, colossal magnetoresistance, quantum magnetism, and other properties somehow emerge from specific assemblies of atoms and molecules. Looking beyond structure to behavior, researchers will study the atomic and molecular bases of such macroscopic properties as friction, flame propagation, and material deformation.

Strongly coupled systems include not only the electronic structures, self-organizing electronic states, phase transitions, and mechanisms of high-temperature superconductivity found in complex materials, but also the coupling of particles and fields in plasmas.

Electrically and magnetically active mixes of electrons and ions have applications ranging from thin films to fusion energy; they span vast stretches of the universe and are critical to the makeup of stars and the character of planets.

Through laboratory experiments and sophisticated simulations, researchers investigate the similarities among classical plasmas and collective quantum-mechanical systems, such as quark-gluon plasmas characteristic of the early universe and neutron stars. Advanced simulations and laboratory plasmas are also used to study magnetic reconnection and other phenomena characteristic of stellar and planetary plasmas. For example, magnetic reconnection accounts for the coronal mass ejections from the sun and can also enable magnetically confined fusion plasmas to escape their “magnetic bottles.” Understanding such complex processes will improve predictions of space weather and the containment of fusion plasmas. Spurred by fusion research, scientists





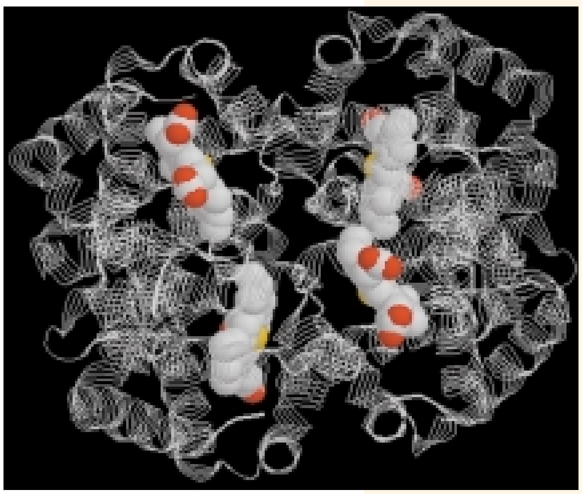
E. Joselevich and C.M. Lieber, Harvard University

Biological systems can be imaged at the level of single molecular building blocks using chemical force microscopy. Scientists at Harvard University have prepared nanotubes tipped with biotin, an enzyme essential to health, as probes for measuring the specific binding pocket of a protein.

Protein Folding

Consider hemoglobin, the large protein that makes blood red. Constructed of two pairs of polypeptide chains, each folded around a ring of atoms holding a single atom of iron, hemoglobin acts like a little spring clip to snap up oxygen atoms in the lungs (where conditions are basic) and release them in the tissues (where conditions are acidic)—taking up carbon dioxide in the form of bicarbonate on the reverse trip.

Each of the four polypeptide chains is wound in eight helical segments, precisely positioning the four iron-containing heme rings within a globular structure. Two of the chains have 141 amino acid residues each, the other two 146; if only one or two of these residues are out of place, oxygen distribution can be crippled, with devastating human results—as in sickle cell disease and the thalassemias. Protein folding has been called the greatest unsolved problem in biology. How can a gene—a linear sequence of information specifying nothing more than the order of amino acids—lay out three-dimensional blueprints for these precise and intricate molecular machines? And how, given the fact that amino acids are strung together by the ribosomes like beads on a string, can innumerable billions of identical copies of the protein fold themselves up perfectly under constantly changing conditions? Early research suggests that there are a wide variety of pathways, within a range of regular phases, by which a string of amino acids achieves its final folded form. How proteins fold under particular circumstances remains a mystery. Unlocking this mystery will require sophisticated modeling on supercomputers and the construction of open, easily accessible databases of amino-acid sequences, protein structures, and bonding mechanisms. Unraveling the mystery of protein folding will allow us to begin to harness the promise of biology for the development of new energy sources and for improving environmental and human health.



NIH

Hemoglobin's four polypeptide chains precisely position its four oxygen-binding heme rings within a globular structure. Devastating human anemias result if only one or two of these amino-acid residues is out of place.

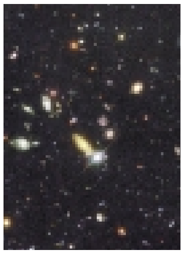
seek to create macroscopically stable high-pressure plasmas in the laboratory.

Thin films, nanocomposites, and biomaterials are among the many intriguing structures with the capacity for self-organization. Scientists will pursue insight into this amazing capacity, as well as ways to control the process.

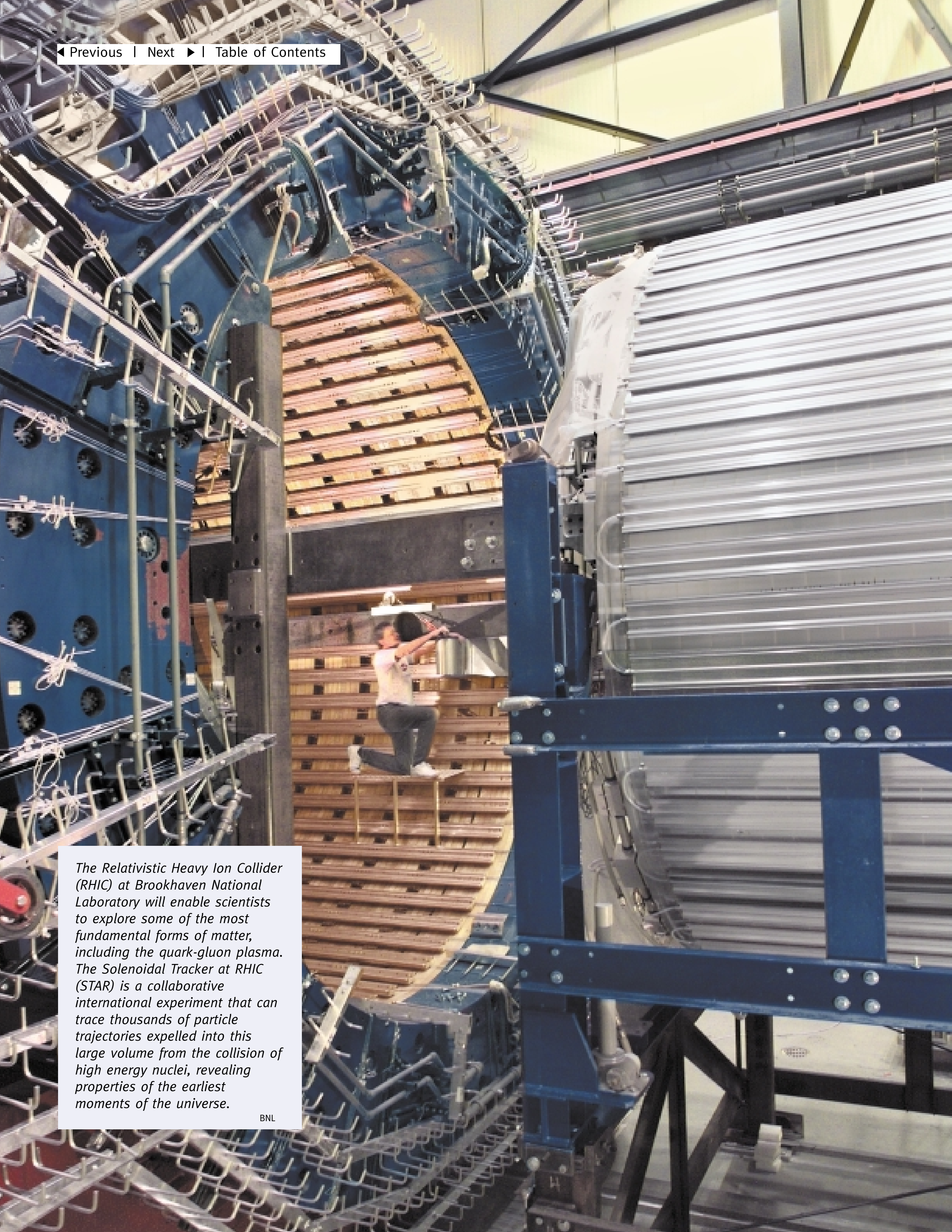
Adaptive systems

Genetic information in linear form is translated into three-dimensional structures of proteins in cells, and cells are organized into complex three-dimensional tissue. How, among all the possible folded states of a string of amino-acid residues, does a protein choose the correct energy conformation state within the cell? We need to know how protein-protein and protein-nucleic acid interactions occur, and how physical and biochemical pathways form a functional organism.

There is much we do not understand about genes and their adaptive mechanisms. For example, we do not know the logic of where a gene begins and ends in an arbitrary length of DNA, and the purposes of introns and DNA with no apparent function—the so-called "junk" DNA that represents more than 90 percent of a human's genetic information. Scientists will seek to determine functional implications from gene sequences alone and how genes and their products work together in chains and networks to accomplish complex outcomes. We will need to enumerate and analyze the variables of dynamic interaction between genes and the environment—how and why cellular structures and tissues are sensitive to slight environmental changes, and whether and how this sensitivity is encoded in genes.



In the coming decades, collaborations among researchers in the national laboratories, universities, other government agencies, and foreign countries will discover new basic particles, manipulate matter an atom at a time, decode the human genome, and understand the function of many unknown genes. The leading-edge research supported by the Office of Science, along with its powerful research facilities and instrumentation, will pave the way for these advances.



The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will enable scientists to explore some of the most fundamental forms of matter, including the quark-gluon plasma. The Solenoidal Tracker at RHIC (STAR) is a collaborative international experiment that can trace thousands of particle trajectories expelled into this large volume from the collision of high energy nuclei, revealing properties of the earliest moments of the universe.

BNL

Provide Extraordinary Tools for Extraordinary Science

NATIONAL ASSETS FOR MULTIDISCIPLINARY RESEARCH

ELECTRONS CUT THROUGH THIN FOILS, CASTING SHADOWS OF ATOMS IN CRYSTALLINE RANKS; A FLOOD OF NEUTRONS TESTS THE INTEGRITY OF TURBINE BLADES; A POWERFUL COMPUTER MODELS AN EXPLOSION OF FLAME IN A DIESEL CYLINDER; BANKS OF ROBOTS TEASE GENETIC DATA FROM DNA; A FLAKE OF SILICON NITRIDE ASCENDING IN A BALLOON SEEKS TRACES OF HEAT FROM THE BIG BANG; A PROTON CIRCUMNAVIGATES A FOUR-MILE TUNNEL AND MEETS ITS ANTI-SELF—AND IN THE DEBRIS OF ANNIHILATION, SCIENTISTS FIND EVIDENCE OF OBJECTS NEVER SEEN. THE REMARKABLE INSTRUMENTS OF SCIENCE, AND THE PEOPLE WHO RUN AND USE THEM, ARE VITAL RESOURCES FOR MEETING THE RESEARCH CHALLENGES OF THE COMING CENTURY.

Many essential scientific objectives can be pursued only by using facilities so specialized, so intricate, or so vast that they could not exist without the participation of the federal government. The Department of Energy plays a unique role in the nation's science enterprise through its support of a broad variety of unique, state-of-the-art user facilities and laboratories, including large accelerators, experimental detectors and reactors, synchrotrons, massively parallel computers, high-capacity networks, and high-resolution microscopes. Thousands of scientists from the national laboratories and from universities, private companies, and other agencies of the U.S. government use these extraordinary facilities to advance the frontiers of knowledge.

In planning, building, and providing for the optimum use of these unmatched assets of scientific research, the Office of Science recognizes three major challenges:

1. To provide world-class research facilities and expertise for exploring the frontiers of the natural sciences
2. To develop scientific simulation for predicting the behavior of complex systems and as a crucial new means of discovery
3. To provide the institutional capacity for strengthening multidisciplinary science by ensuring the best possible tools and people to do the nation's research, now and in the future

Instrumentation for the Frontiers of Science

Objective 1: Provide leading research facilities and instrumentation to expand the frontiers of the natural sciences

Myriad scientific advancements of the past half-century have derived from research conducted with the scientific instrumentation provided by the Office of Science. Theories are tested against the empirical world in facilities dedicated to experimentation, analysis, and discovery—instruments that open the door to understanding matter, energy, and the processes of life.

Our strategies in providing research facilities emphasize accelerators and detectors for high-energy and nuclear physics; synchrotron light sources and neutron beam facilities; and more specialized scientific facilities such as those for fusion, electron-beam microcharacterization, combustion, and biological and environmental research. Above all, we are committed to maintaining and improving these extraordinary tools and to ensuring their accessibility and usefulness to the nation's scientific community.

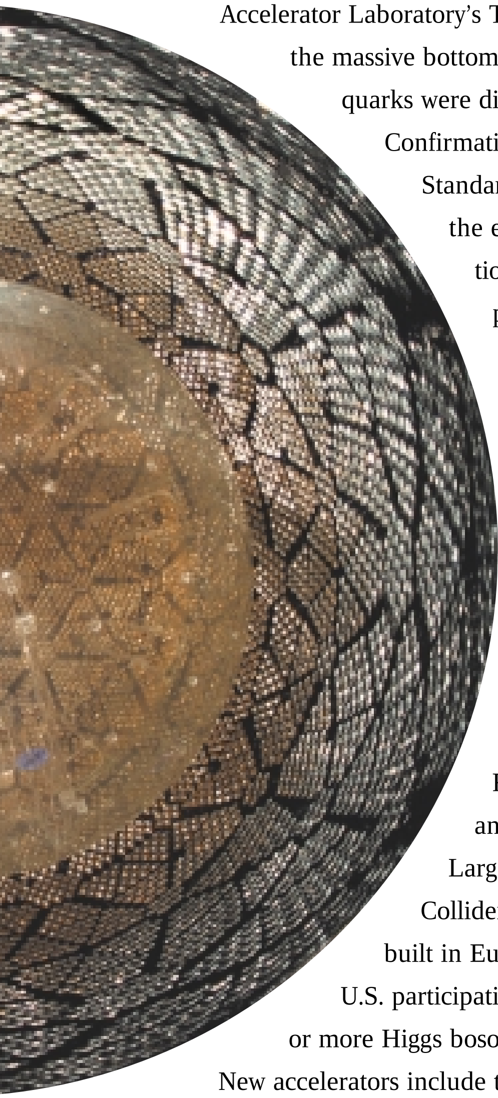
FNAL

In the four-mile circumference tunnel at the Fermi National Accelerator Laboratory, the Tevatron accelerator (situated below the now retired Main Ring), is delivering precise measurements within the Standard Model and searching for physics beyond it. The high intensity from the new Main Injector is essential for this new physics.

Accelerators and detectors for high-energy and nuclear physics

The Standard Model of Fundamental Particles and Interactions is one of the great intellectual achievements of the 20th century. Just as powerful accelerators, using electrons, protons, and other subatomic particles, were used to probe inside the atom and led to the discovery of subatomic particles, so experiments using new instruments in particle, nuclear, and astrophysics now provide exciting glimpses into the fundamental reality of what the world is made of and how it works.

For example, at the Fermi National Accelerator Laboratory's Tevatron, the massive bottom and top quarks were discovered. Confirmation of the Standard Model—the explanation of why particles have any mass at all—awaits the discovery, being pursued both at Fermilab and at the Large Hadron Collider being built in Europe with U.S. participation, of one or more Higgs bosons.



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New accelerators include the Continuous Electron Beam Accelerator Facility, the Relativistic Heavy Ion Collider, and the Asymmetric B-Factory. These machines are being used to investigate quarks in nuclei, search for free quarks in quark-gluon plasmas, and study violations of symmetry in the weak interaction of fundamental particles.

DOE is a leading participant in the international Sudbury Neutrino Observatory. Suspended in a 10-story tall underground chamber, the 10,000 photomultiplier tube array will detect photons given off as neutrinos pass through the plastic sphere that holds 350 tank cars of heavy water, revealing oscillations among the flavors of neutrinos emitted from the Sun.

The future exploration of high-energy physics will require new generations of accelerators. The Office of Science strategy supports further international collaborations for the design of "the next linear collider," which will eventually reach a center of mass energy up to 1.5 TeV. Exploration of other new accelerator concepts is also of value for advances in particle physics, such as a possible muon collider. For nuclear physics, an accelerator of high current radioactive beams offers the prospect of revealing the structure of unstable nuclei.

To overcome future limits, accelerators may make use of lasers, plasmas, and very-high-frequency radio sources to accelerate charged particles; advanced superconducting materials and new geometries may be used in superconducting magnets for particle-beam optical systems; and beam sources will operate at higher currents and higher brightnesses.

Exquisitely crafted particle detectors reveal the new phenomena created at accelerators, detecting and reconstructing the particle trajectories that provide evidence of collision events. The Gammasphere and the Fragment Mass Analyzer at the Argonne Tandem-Linac Accelerator System (ATLAS) now provide detailed information on the dynamics of nuclear structure. The ATLAS Detector will provide evidence for the Higgs boson at the Large Hadron Collider. The Liquid

Scintillation Neutrino Detector at Los Alamos will search for neutrino oscillations—as will the Sudbury Neutrino Observatory, a giant detector for an accelerator none other than our Sun.

New detectors to be supported by the Office of Science will also need to overcome limits. Still more sensitive detectors must be devised, capable of rapid response with the lowest possible noise, often under the most extreme conditions imaginable: energetic signals from particles that must be sorted on the fly as they flood giant detectors by the trillions under hard radiation; signals from neutrinos, ubiquitous next-to-nothings that penetrate miles of solid rock; signals from the early universe, so rare and faint they barely rise above quantum interference.

Scientific users and equipment crowd the National Synchrotron Light Source at Brookhaven National Laboratory. High demand for synchrotron light sources operated by the Office of Science has created a waiting list of qualified scientists seeking access to the high-intensity, high-quality photon beams.

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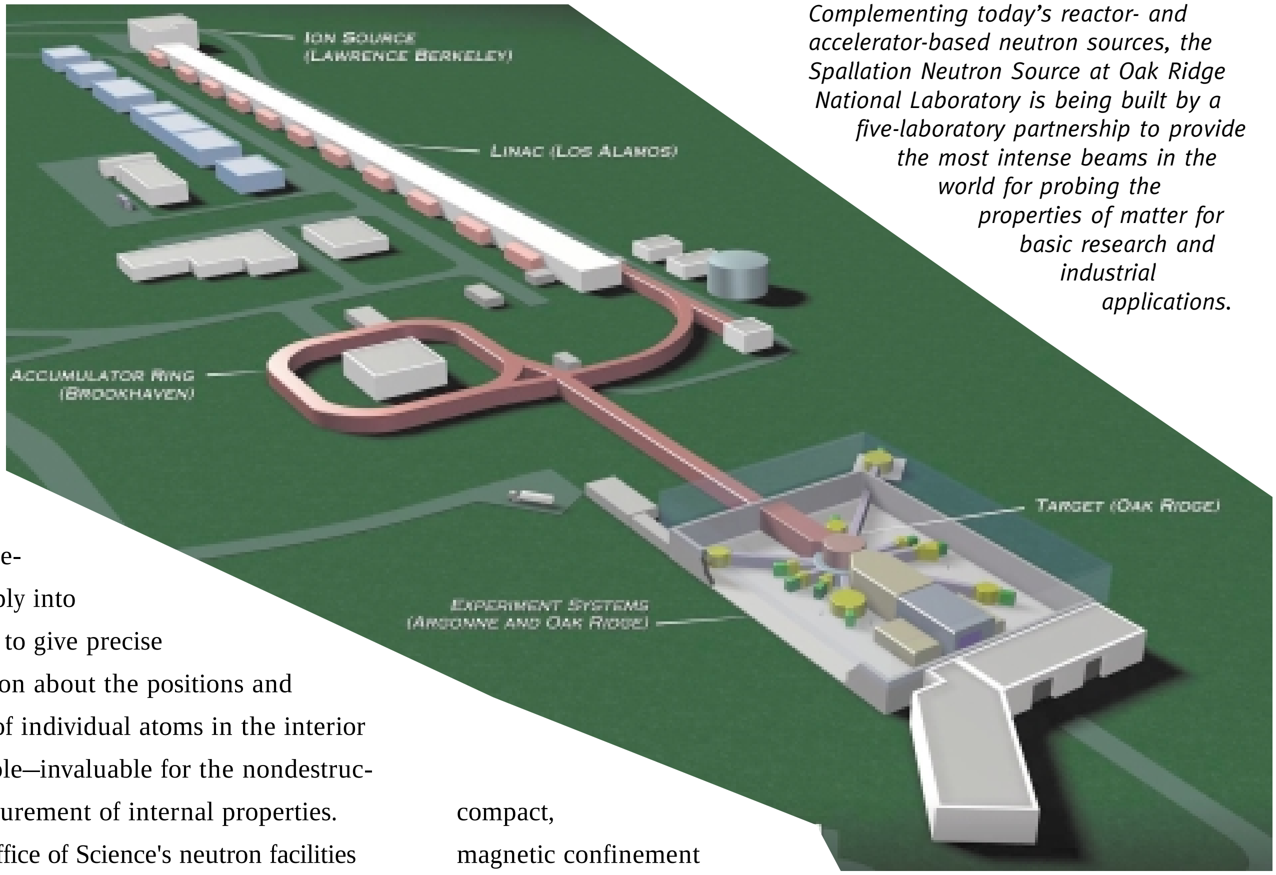
Light sources and neutron beam facilities

Synchrotron light and neutron beam facilities help improve our understanding of the natural world through their interactions with bulk material and molecules, atoms, and ions. They probe the structure of materials and living systems at atomic and molecular levels or larger, revealing countless mysteries of how things work. Examples include the determination of the three-dimensional arrangement of atoms in DNA, proteins, and viruses and the molecular-level examination of ceramics and semiconductor materials, essential to the development of designer materials for new technologies.

Synchrotron radiation provides an intense source of tunable light over a broad range of frequencies, from the infrared to the hard x-ray. So great is the scientific interest that the available beams at the Stanford Synchrotron Radiation Laboratory, the National Synchrotron Light Source at Brookhaven, the Advanced Light Source at Berkeley, and the Advanced Photon Source at Argonne have all been oversubscribed. To add more beamlines and endstations and improve temporal and spatial resolution and signal strength, the Office of Science will improve its existing synchrotrons and study the building of even more advanced machines.

Neutrons, ordinarily thought of as particles, also have—like all entities described by quantum mechanics—wave-like characteristics. Massive and electrically neutral,



Complementing today's reactor- and accelerator-based neutron sources, the Spallation Neutron Source at Oak Ridge National Laboratory is being built by a five-laboratory partnership to provide the most intense beams in the world for probing the properties of matter for basic research and industrial applications.

ORNL

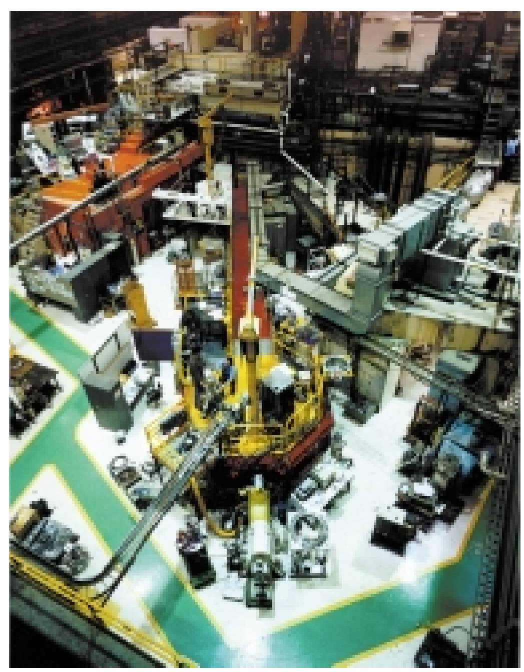
neutrons penetrate deeply into materials to give precise information about the positions and motions of individual atoms in the interior of a sample—invaluable for the nondestructive measurement of internal properties.

The Office of Science's neutron facilities are the High Flux Beam Reactor at Brookhaven, the High Flux Isotope Reactor at Oak Ridge, the Intense Pulsed Neutron Source at Argonne, and the Los Alamos Neutron Science Center. A much more intense version of this last machine, the Spallation Neutron Source, being built at Oak Ridge National Laboratory as a collaboration of five national laboratories, will accelerate a milliamp of protons—eventually five milliamps—to an energy of one GeV.

Specialized scientific facilities

Many of the Office of Science's primary research missions can only be pursued through specialized programs and facilities.

Fusion research requires investigation of fundamental problems in plasma physics and engineering solutions. The National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory has been built to investigate an innovative, compact, magnetic confinement configuration in which plasma pressure is expected to be especially high. Other important facilities now operating include the DIII-D facility operated by General Atomics in San Diego, and the Alcator C-Mod facility at MIT. Improved particle and power handling should reduce demands on the components of the reactor facing the plasma and inertial fusion energy drivers



The Intense Pulsed Neutron Source at Argonne National Laboratory provides scientists with beams of cold neutrons for measuring atomic position, motions, and surface properties of many materials. The facility has been serving the scientific community since 1981.

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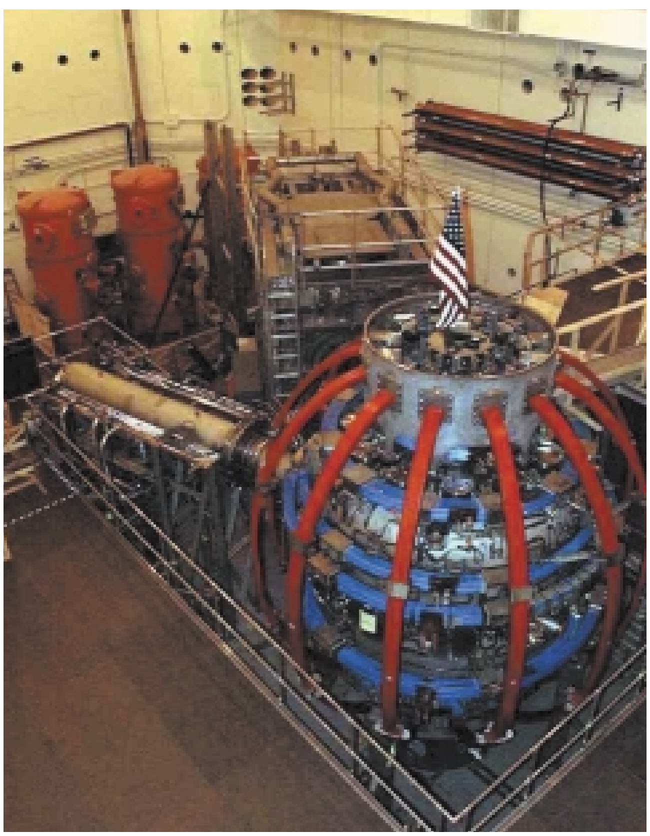
Experimental, theoretical, and computational studies of magnetically confined plasmas underlie the design and fabrication of test fusion reactors such as the National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory.



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which would use accelerated ions or beams of photons to implode a fusion fuel pellet.

The Office of Science will continue to develop facilities to understand the physics of plasmas and to identify and explore the innovative and cost-effective paths to fusion energy. There are several approaches to fusion, from the tokamak, to alternative magnetic configurations, to inertial confinement using particle beams or lasers. The Office of Science will seek a consensus among the key elements of the scientific community in defining the pathways for advances in fusion science and energy for a growing world population.

Electron-beam microcharacterization centers provide transmission, scanning, analytical, atomic-resolution, high-voltage, and other electron microscopes—as well as other microscopy techniques and tools—to users on-site and through interactive networks. Anticipated research directions require that the centers provide specialized services to characterize the structure of materials and their dynamics at resolutions of one angstrom or better—the nanostructural scale at which the detailed behavior and performance of materials is determined.

At the Combustion Research Facility at Sandia, Livermore, researchers study turbulence, energy-transfer phenomena, spectra for diagnostic probes, chemical reaction rates under high temperatures and pressures, and other combustion phenomena.

Other special-purpose centers include the Center for X-Ray Optics and the Center for Advanced Materials at Berkeley, the Surface Modification and Characterization Facility at Oak Ridge, and the National High Magnetic Field Laboratory at Los Alamos.

The Office of Science plans to maintain and strengthen its specialized facilities for biological and environmental research, providing new facilities based on strategic assessments of scientific needs.

Molecular-level environmental sciences are pursued at the Environmental Molecular Sciences Laboratory at Pacific Northwest National Laboratory. This and related facilities at other institutions must be maintained at the leading edge for studies that range from enzymatics of soil microbes to the properties of cometary ice.

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Joint Genome Institute

The Joint Genome Institute has combined the resources of three national laboratories for high throughput production sequencing. DOE, in partnership with the National Institutes of Health and industry, plans to complete rough and final drafts of the sequence early in the next decade.

Biological and environmental research is conducted at dedicated beamlines and equipment stations at synchrotron light sources and neutron sources. Structural biology research facilities investigate protein structure at sub-angstrom scale. The synchrotron beamlines provide structural information in a shorter time and with much sharper detail than conventional sources of x-rays. Beamlines for structural biology are important to the scientific programs of the Spallation Neutron Source.

The Production Sequencing Facility (PSF), which began operation in 1999, is a key element of the Joint Genome Institute. PSF is becoming a high-throughput DNA-sequencing factory that will continue to apply cutting-edge sequencing technology, automation, and information management techniques to achieve national human genome sequencing project goals early in the next decade. Facilities for comparative and functional genomics, including mouse genetics, will be vital for serving the biological research community.

The Atmospheric Radiation Measurement program maintains observation sites in the Southern Great Plains, the Western Pacific, and the North Slope of Alaska, gathering data on solar (incoming) and infrared (outgoing) radiation to improve the modeling of clouds and radiation in general circulation climate models.

Free Air Carbon Dioxide Enrichment (FACE) sites study the impacts of future elevated levels of carbon dioxide in the environment by releasing controlled amounts of carbon dioxide, not harmful to plants, and monitoring the response.

OBJECTIVE 2: ADVANCE COMPUTATION AND SIMULATION AS CRITICAL TOOLS FOR SCIENTIFIC DISCOVERY

Supercomputers extract what cannot otherwise be gained from theoretical equations and what cannot otherwise be found in experimental data. They allow us to simulate and test our understanding of the behavior of complex systems, including the response of such systems to altered conditions. They let us see processes we could never have observed and materials that don't yet exist. Efficient data communication to users around the world multiplies the power of scientific computation; this realization led high-energy physicists to invent what became the World Wide Web.

Scientific computation has already taken its place alongside experiment and theory as a third mode of discovery. Yet scientific software and the hardware to run it have only begun to fulfill their research promise.

The strategy for achieving our scientific simulation and computation objective is threefold: to foster the development of science applications software; to promote new ultra-high performance computation and communications facilities; and to support computer science and related enabling technologies to achieve the higher performance levels required for ever more challenging computational problems.

Science applications software

The Office of Science will further advance research on the underlying mathematics and numerical algorithms needed for effective description and prediction of physical systems and processes. Areas include mathematical physics, differential equations, control theory, wave theory, fluid dynamics, dynamic systems, geometric and symbolic computing, and linear systems and optimization.

The research will address new programming models and performance tools, including visualization, parallel program

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National Energy Research Scientific Computing Center provides high-performance computing tools and expertise that enable computational science of scale, in which large interdisciplinary teams of scientists attack fundamental problems in science and engineering that require massive calculations.

debugging and performance tuning, and runtime management.

The results of this research will be applied to integrated sets of software tools that can be used by scientists in many disciplines for high-performance scientific applications.

Ultra-high performance computation and communications facilities

Massively parallel computers are becoming essential to scientific computing. The Office of Science will accelerate research efforts to meet the scientific, mathematical, and engineering challenges raised by these giant machines. Significant development efforts will focus on new technologies to make petabyte data sets and peta-scale computers easily accessible.

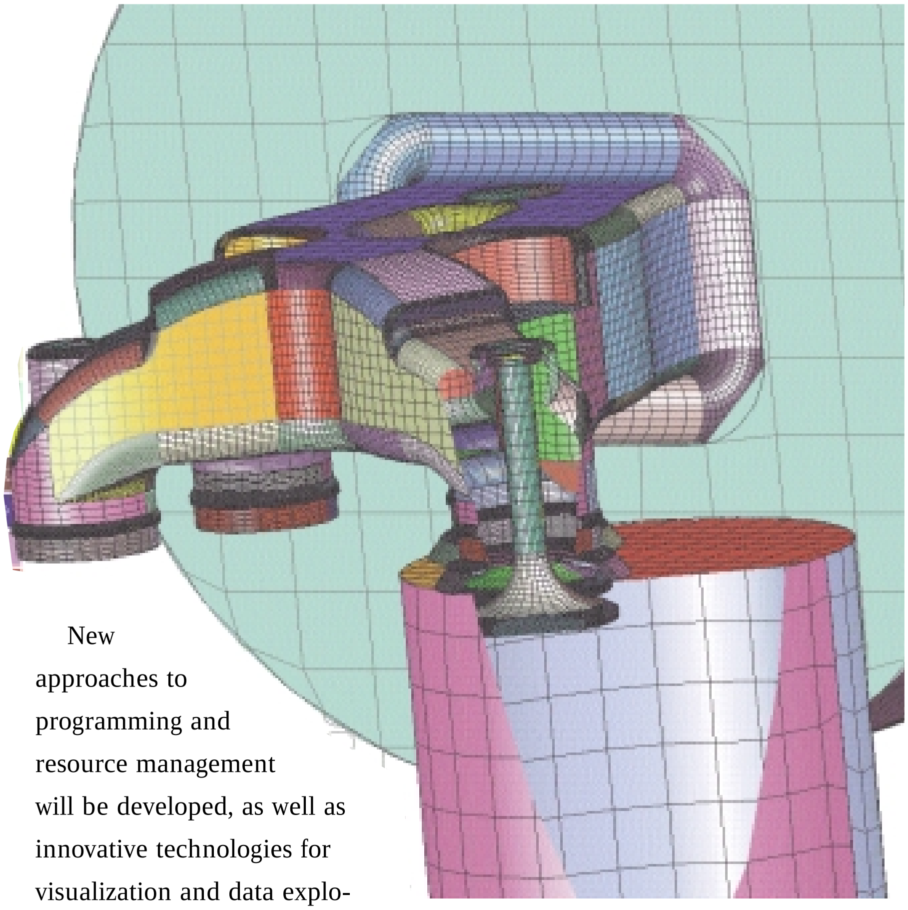
Research will also address advanced security systems, new kinds of electronic notebooks and conferencing modules to aid far-flung collaborations, and high-resolution virtual reality systems as tools for information sharing.

Computer science and enabling technologies

As scientists attack new and more challenging computational problems, new generations of more effective and efficient means to achieve needed performance must be developed. These performance levels require the transition from giga- to tera- to peta-scale computing and communications. To make these transitions, alternative computer architectures and networking technologies must be investigated and their benefits and limitations assessed.

New approaches to programming and resource management will be developed, as well as innovative technologies for visualization and data exploration. The Office of Science will foster the development of new technologies including parallel discretization, scalable numerical algorithms, and uncertainty technologies that promise dramatically enhanced capabilities for solving complex scientific and engineering problems.

Meanwhile researchers will investigate other fundamental methods, such as faster electronic materials, x-ray lithography for greatly reduced feature size, and the potential for quantum computation, that may someday revolutionize scientific computing even more than massively parallel processing has done.



Diesel Collaboratory

Simulating combustion requires modeling complicated chemical dynamics inside equally complicated spaces. The "composite overlapping grid" approach maps regions of complex geometry with curvilinear components, each of which reduces to a rectangle.

Objective 3: Strengthen the nation's institutional and human resources for basic science and multidisciplinary research

The Office of Science bears a fundamental responsibility to maintain the nation's foremost research facilities and programs in many fields; to train and support the next generation of the nation's scientists and engineers; to educate its sponsors and the general public about the many aspects of energy that touch all our lives; and to cooperate with other agencies, universities, and private industry to sustain scientific and technological progress.

Our strategies for meeting this objective focus on the national laboratory system; on disciplines, such as high-energy and nuclear physics, that are essential to the DOE mission; and on science education. We also seek to benefit from a broader diversity in research performers throughout the nation.

Undergraduate and graduate students work side by side with researchers at Argonne National Laboratory, preparing the next generation of scientists and engineers.

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National laboratory system

National laboratories supported by the Office of Science conduct fundamental research and development, often requiring years of sustained effort by multidisciplinary teams. They design, construct, and operate the most powerful and specialized scientific facilities of our time, facilities that offer solutions to mysteries across a range of disciplines. In no other setting do researchers have access to technology so sophisticated. Capabilities in instrumentation not only serve the objectives of DOE, but they also provide, for example, the detector systems and instruments deployed by other agencies, including NASA, the National Institutes of Health, and the National Science Foundation.

Our strategy is to continue making prudent investments to maintain laboratory infrastructure and competencies; to manage the laboratories as an integrated system; and ensure that they continue to increase their value and service to investigators from universities, other government agencies, and industry. Our contributions to making the Internet more robust and to connecting remote virtual laboratories will improve the utilization of the nation's scientific resources and unify its research efforts.

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Students are highly interested in observing the formation of plasmas and their properties at the Princeton Plasma Physics Laboratory.

Disciplines essential to our missions

The Office of Science shoulders the responsibility for maintaining research communities and their institutions essential for fulfilling the unique missions of DOE. The Office of Science serves as the nation's primary or sole supporter of a number of important disciplines, including high-energy physics, nuclear physics, plasma science, genomics, environmental and ecological research, chemistry, and materials science. Maintaining these capabilities, and those for other essential disciplines, will continue to be a vital strategy for the Office of Science.

Science education

Every year many hundreds of graduate students complete their degrees at national laboratories and user facilities, and hundreds more do their first independent research as postdoctoral fellows at these facilities. Hands-on experience at the national laboratories has inspired tens of thousands of undergraduates to continue their academic majors in science and engineering at a time when many of their fellow students drop out. The Office of Science will continue to support these undergraduate and graduate students and postdoctoral fellows through internships, research grants, and fellowships.

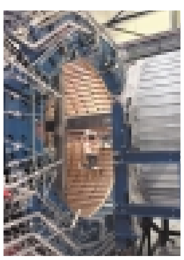
Through a variety of programs for schools and on the Internet, the Office of Science also reaches out to elementary and high school teachers and students, and to adults with an interest in science. Wall charts explain such topics as particle physics, nuclear physics, and fusion research, while publications describing research activities and interactive virtual laboratories are made available on the Web.

Broadening the scope of research performers

The Office of Science is dedicated to enhancing the effectiveness of the nation's researchers, whether public or private, from broad geographic regions and from a diversity of backgrounds and cultural settings. Office of Science programs serve more than 15,000 university scientists from diverse institutions. Significant segments of our research programs are directed toward university performers, enabling these programs to benefit from the scholarship of these scientists; to enrich the science at academic institutions; and to invest in the future through the support of undergraduate, graduate, and postdoctoral students.

The Office of Science will continue to promote participation in these programs by diverse university performers, including minority institutions. Through this diversity, we gain new perspectives and approaches for science to serve our nation.

Additionally, we will encourage small businesses to provide innovative technologies to federal research and development programs through grants, awards, and collaborations in a wide variety of fields including accelerator science, molecular design of nanoscale materials, biotechnology, and computer science.



THE EXTRAORDINARY TOOLS SUPPORTED BY THE OFFICE OF SCIENCE ARE INTIMATELY CONNECTED TO THE RESEARCH PROGRAMS AND GOALS OF THIS STRATEGIC PLAN. THE MAJOR FACILITIES PRODUCE SOME OF THE MOST EXCITING RESULTS OF OUR PROGRAMS, DISCOVERING THE FUNDAMENTAL CONSTITUENTS OF MATTER, UNLOCKING THE STRUCTURES OF LIVING SYSTEMS, ENABLING THE ANALYSIS OF THE ENVIRONMENT, AND LEADING TO SOURCES OF UNLIMITED AND CLEANER ENERGY. THEY SERVE THOUSANDS OF INVESTIGATORS IN UNIVERSITIES, GOVERNMENT, AND INDUSTRY, AND GIVE MANY PROSPECTIVE RESEARCHERS THEIR FIRST EXPOSURE TO WORKING SCIENCE.

Manage as Stewards of the Public Trust

SCIENTIFIC AND OPERATIONAL EXCELLENCE

THE IMPERATIVE HAS NEVER BEEN GREATER TO DELIVER THE MOST VALUABLE RESEARCH WITHIN AVAILABLE BUDGETS. WITH REDUCED INDUSTRY INVESTMENT IN LONG-TERM BASIC RESEARCH, GOVERNMENT PROGRAMS ARE BEING CALLED UPON TO DELIVER MORE FOR LESS AND TO ASSUME MORE OF THE BURDEN FOR THE LONG-TERM WELL-BEING OF THE NATION'S SCIENCE INTERESTS.

Research investment strategies must be sound, possess the highest degree of integrity, and be responsive to the communities they serve. Operations must be conducted in a fiscally responsible manner, with appropriate attention to the safety and well-being of workers, local communities, and surrounding environment. These and other commitments to management excellence will continue to engender the trust that is needed and the confidence that is necessary to manage an effective science enterprise.

The Office of Science has a commitment to the American people to make wise decisions on scientific investments, to be responsible stewards by protecting our employees and the public, and to manage our resources effectively and efficiently.

Our goal in managing programs, field offices, and facilities for the public trust addresses many key questions, among them: How can the best scientific work be chosen and supported? How can safe and efficient management of the nation's resources be ensured? How do we maintain a quality workforce to ensure the on-going success of our efforts?

To address these questions we have formulated the following objectives and strategies:

1. To pursue the highest standards of scientific excellence and relevance
2. To distinguish our facilities and operations as models of safety, health, and environmental protection
3. To manage our operations and human resources for high performance and efficiency

Objective 1: Pursue the highest standards of scientific excellence and relevance

The Office of Science will further this objective through four strategies. First, we continue to strengthen our peer review process for evaluating new ideas for basic research. Second, we will strengthen our planning, guidance, and coordination of current and future scientific programs and research. Third, we will promote the integration of basic and applied science through research partnerships among national laboratories, government agencies, universities, and industry. Fourth, we will foster a culture of creativity in research environments.

Peer review and merit evaluation

Excellent basic research produces new knowledge and ideas that endure, that change the way people think and act. The public is served by the value of new ideas and knowledge, their impact on products and processes, and their enrichment of our culture. Managing for excellence in basic research—for new knowledge and ideas—is tantamount to managing for discovery and technical creativity.

How can the best ideas be selected? Every major organization that supports basic research has faced this challenge. Over the years, peer review has emerged as the dominant—indeed perhaps the only—valid tool for measuring the technical excellence of basic research.

Extensive use of the formal peer review process, conducted by leading scientists, will continue to be the strategy employed by the Office of Science for its extramural grant program, internal research programs, and the scientific user facilities. These regular merit reviews of all research activities will continue to yield meaningful returns on an investment of time, materials, and thought, and to lay the groundwork for breakthroughs.

Scientific advice and planning

To ensure research relevance, the Office of Science sets strategic directions through close relationships with other DOE programs and by promoting the exchange of ideas between and within basic and applied research communities. Science program review committees consist of representatives from universities, government, and industry. Advisory groups and steering committees with similar cross-cutting membership are increasingly important for setting research directions. The recommendations of these advisory groups reach the highest levels of decision-making within the Office of Science.

Beyond addressing fundamental science missions, the advisory groups support DOE's overall mission by helping to integrate the basic research of the Office of Science with DOE's applied research and development efforts.

Program coordination will continue to be aided by DOE's standing committees and interagency and international coordinating committees. For large projects the planning, construction, and operation of scientific facilities will continue as open processes, with leading scientists and technologists serving on advisory panels for every project the Office undertakes.

Research coordination and partnerships

The Office of Science fosters the integration of basic and applied research through the formation of "real" and "virtual" laboratories that bring together researchers with different backgrounds and expertise on a range of problems. The Diesel Collaboratory and the Virtual National Laboratory on Extreme Ultraviolet X-ray Lithography are examples of major partnerships that bring the expertise of DOE scientists to bear on maintaining the technological leadership of the United States. The national laboratory system will continue to play a special role in the ability of the Office of Science to effectively integrate basic and applied research by providing opportunities to collocate activities. Also, the national laboratories will under-

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The Workshop on Complex and Collective Phenomena sponsored by the Office of Basic Energy Sciences brought together more than 100 leading scientists to help define a new scientific initiative for the Office of Science.

take more joint efforts to make complementary use of the competencies at different sites.

Partnerships across agencies and institutions will continue to be necessary to deliver the greatest scientific benefits. Global climate change, information technology, genomics, and high-energy physics are examples for which multi-agency effort and coordination can best mobilize and sustain the nation's scientific resources.

International collaboration is becoming more important because of the powerful new methods and associated high instrumentation costs in many scientific fields, including high-energy and nuclear physics, biological sciences, and fusion energy. Projects such as the Large Hadron Collider, the Relativistic Heavy Ion Collider and the Human Genome Program depend on international participation and coordination. Our strategy is to continue to support such collaboration where justified by scientific need, breadth of effort, or opportunities for cost sharing.

The United States is a major participant in the Large Hadron Collider at CERN in Europe. DOE scientists have key roles in the accelerator system components, represented in this test segment, and in the detector systems at the facility. This international collaboration enables large-scale physics experiments not otherwise possible with the resources of a single nation.

CERN Photo

Culture for creativity

In our pursuit of excellence, the Office of Science seeks to create an environment in which excellence is not only rewarded, but expected and even planned. For example, beyond sponsoring the Enrico Fermi and E.O. Lawrence Awards for outstanding performers, the Office has initiated studies to explore the environmental differences in basic and applied research and technology development that lead to excellence; and to compare and contrast research environments in national laboratories, universities, industries, and other types of institutions in the United States. With the results of these studies, the Office will improve its management of research programs by increasing incentives and reducing impediments, while strengthening the relationships among researchers. The Office's institutional reviews and program visits will continue to provide a first-hand view of the research environment and an opportunity to improve the infrastructure and climate for research.

Protect Workers, the Public, and the Environment

Objective 2: Distinguish our facilities and operations as models of safety, health, and environmental protection

Our strategies for achieving this objective include (1) the pervasive application of Integrated Safety Management Systems and (2) a commitment to fostering communications and good relations with communities that have a stake in our work.

Integrated Safety Management

Science often involves working at extreme energies and pressures, with dangerous processes and materials. It is imperative that the Office of Science integrate health, safety, and environmental protections into its operations to ensure the safety of those who conduct its work, the well-being of local communities, and the protection of the environment.

The Office of Science has adopted Integrated Safety Management Systems as its underlying strategy and policy framework, systematically building safety measures into all research programs, from initial planning through execution. The strategy is integrated into individual responsibilities at all levels of every program, facility, and institution supported by the Office of Science.

The Office insists that its scientists match the creativity to pursue science with the discipline to ensure safety and protect the environment. Research funds will be applied as necessary to ensure that all activities are conducted safely and in an environmentally conscientious manner, and that researchers take up lessons learned and best practices from throughout the scientific community.

Communications and community relations

Scientists need to talk not only to one another, but also to the people who live where they work, the people who support their work through taxes, and the people affected by their results. Office of Science officials and laboratory and facilities managers need to communicate their plans, expectations, disappointments, and successes to their own personnel, to local communities and industry partners, and to state and national representatives. Our strategy is to build constructive relationships and strengthen communication with local community members, to learn of their concerns, inform them of the changes taking place at our facilities, and develop cooperative solutions to problems.

We also make our activities and scientific and technical information readily accessible to all scientists and the public in all sectors and institutions. One critical example of this effort is our application of information technology to create fully electronic virtual libraries, maximizing access to programs and their accomplishments.

Management Effectiveness and Efficiency

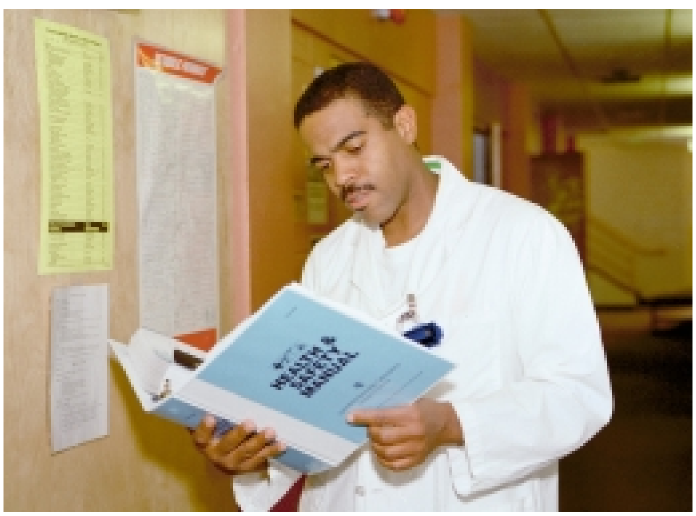
Objective 3: Manage our operations and human resources for high performance and efficiency

Our strategies for achieving this objective are performance-based management, streamlined operations, award-winning construction management practices, and a trained, effective work force.

Performance-based management

The Office of Science supports the principle of performance measurement as the critical strategy for managing its programs and research performers. The Office supports and will implement the recommendations made by the National Academy of Science for the evaluation of basic research under the Government Performance and Results Act. Basic research can be evaluated meaningfully on a regular basis, and these evaluations can be made against the goals and program objectives of the Office of Science. For basic research, quality, relevance, and leadership continue to be the primary assessment criteria, and expert review the primary assessment method.

The Office of Science will also assess the stewardship of its researchers, institutions, user facilities, and program management through peer review, quantitative indicators, customer evaluation, and stakeholder input. These assessments may include cost/benefit studies, case studies, historical retrospectives, and annual program highlights.



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Safety training is among the many instructional programs supported at the national laboratories. These programs enable safe operations, outstanding performance, and career development at DOE facilities.

Streamlined operations

The Office of Science, dedicated to efficient and responsible operations, has realigned its field reporting structure and is working with field offices and laboratories to deliver more cost-effecive research managment.

For example, during the past several years we have significantly improved the metrics used to assess the cost effectiveness of the national laboratories. We will build on this and other recent initiatives to improve information management systems and to develop activity-based management control of operations.

Through its Multiprogram Energy Laboratories–Facilities Support program, the Office of Science has invested over $400 million in the last 20 years for construction to replace, upgrade, and renovate the general-purpose infrastructure at the multiprogram laboratories.

The Laboratory Operations Board will continue to focus on improved management practices as the Office of Science leads the effort to streamline oversight of the laboratories, moving from multiple DOE layers to management based on constructive partnerships among sponsors and performers. The Office will continue to pusue opportunities that strengthen manament and communications, in order to seamlessly link research performers, field elements, and headquarters.

Award-winning construction management practices

The Office of Science is world-renowned for building user facilities on schedule and within budget. Examples in recent years are the Relativistic Heavy Ion Collider at Brookhaven, the B-factory at the Stanford Linear Accelerator Center, the Environmental Molecular Sciences Laboratory at Pacific Northwest, the Advanced Photon Source at Argonne, the Advanced Light Source at Berkeley, and the expansion and upgrade of the Combustion Research Facility at Sandia, Livermore.

A key to award-winning construction management practices is the set of review processes established by the Office's Construction Management Division. This independent division advises the director of the Office of Science on the construction and operation of major research facilities.

The Office of Science will continue to refine and improve its methods, while helping others to adopt some of these best-in-class practices.

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The Office of Science constructs major scientific facilities such as the Advanced Photon Source (APS) at Argonne National Laboratory. The APS, whose accelerator tunnel is shown here under construction, is now among the most powerful sources of hard x-rays in the world. The APS was constructed within scope, schedule, and budget.

Trained and effective work force

The Office of Science seeks to cultivate the variety of skills and perspectives needed for science and technology leadership. The success of this strategy will require support and training for employees, meaningful rewards and recognition, and over the long term stronger programs to ensure that technical managers and staff remain current in their respective scientific fields. It will also require the Office to continue to value the richness, experience, and imaginative ideas contributed by a diverse work force.

We will continue to seek effective ways to reward employees based on their performance and to provide the necessary training to ensure that our work force can achieve the goals and objectives of this plan.

Success Indicators

What will the world of science be like 20 years in the future? Although outcomes are difficult or impossible to predict, the Office of Science cites the following examples of accomplishments as indicators of success for the strategies set forth in this strategic plan. These indicators represent a small fraction of the wealth of knowledge that will result from achieving our goals. In fulfilling our mission, we will ensure that the research performed by our investigators is recognized as outstanding through rigorous peer review. We will continue our strong tradition of earning some of the most prestigious awards in science and meriting the accolades of those who use our results and benefit from our programs.

Fuel the Future

- Development of novel hydrogen-related surface chemistry that can lead to more efficient methods for hydrogen production and storage and increased use of hydrogen both as a primary fuel and in fuel cells
- Understanding the patterns in gene sequence and protein structure that enable the prediction and control of microbial and plant processes, this achievement could leading to bioengineered plants and microbes that convert low-grade fossil fuels, agricultural waste, and other feedstocks to clean, carbon-based, alternative fuels
- Advances in the theory of superconductivity and in the molecular synthesis of superconducting materials, leading to superconducting devices that operate at higher temperatures and to systems for more efficient storage and transmission of electric power
- More adaptable, higher-resolution seismic instrumentation, including new sources and detectors, and computer algorithms for tomographic imaging that can better identify hydrocarbon reservoirs and subsurface transport pathways
- Better electrolyte chemistry and improved understanding of ion solutions and surface chemistry, leading to anodes and cathodes for longer-lasting, higher-capacity, rechargeable batteries—even thinner and lighter than plastic wrap
- Greater predictability and control over structural materials at the atomic level, leading to lighter, stronger, better-insulating materials for more efficient transportation systems, buildings, and machinery
- New materials for semiconductors, thin films, and coatings, and new electrical and optical systems to multiply the efficiency of natural and artificial lighting systems
- Photochemical systems that hold promise for economical, highly efficient solar cells
- New and innovative metals and ceramics, designed at the atomic level, for use in manufacturing processes and power production
- Confinement of plasmas through experimental systems, leading to cost-effective net power production from fusion

Protect Our Living Planet

- Fast, accurate sensors and diagnostics for tracking pollutants through the atmosphere, waterways, and subsurface
- Modified microbial enzymes that can operate in extreme environments to clean up radioactive waste and toxic pollution, improve processes for the recovery of metals and other valuable commodities, and modify and upgrade fuel stocks
- An accurate, high-resolution, multidimensional biogeochemical model that can project worldwide carbon sources and predict the sequestration pathways and reservoirs of carbon in the biosphere
- Precise and accurate understanding of reaction chemistry and turbulent flow modeling to control the production and separation of carbon, hydrogen, nitrogen, and other compounds from combustion products and industrial wastes
- High-spatial-resolution, multidimensional computer models of biogeochemistry, physics, and climate to enable regional and global predictions from years to centuries
- Understanding of the biomolecular effects of low-dose radiation to establish science-based limits for human and environmental exposure to hazardous energy by-products, taking into account individual and genetic susceptibilities
- New high-affinity metabolic labels and imaging detectors for medical diagnosis, including the computational algorithms for high-resolution, three-dimensional reconstructions and motion pictures of normal and diseased metabolism
- Tailor-made pharmaceutical agents and beam delivery systems for the treatment of inoperable cancers and disease

Explore Matter and Energy

- A coherent model of the origin and fate of the universe, supported by and consistent with observations of neutrino mass, cosmic background radiation, distant quasars and supernovas, and dark matter
- Discovery of the Higgs boson, or bosons
- Fundamental evidence for charge-parity symmetry breaking and the prevalence of matter over antimatter
- Discovery of the first supersymmetric particles
- Theoretical unification of the electroweak force with the strong nuclear force and gravity
- Fundamental understanding of plasma transport and the control of turbulence in a confining magnetic field
- Predictive models for the optical and electronic behavior of atoms and molecules that can lead to the development of materials with properties never observed in nature

- New insight into the nature of magnetic phenomena, leading to ultra-dense, multilayered magnetic storage devices
- Optical, ion, and plasma beam technology that can lead to electronic circuitry ten times denser than that on today's chips
- Self-assembled nanomaterials with new and useful optical, electrical, thermal, chemical, and physical properties
- Ability to understand and predict the three-dimensional structure and behavior of cells and tissues to better engineer targeted drugs, biosensors, medical implants, and other biocompatible agents
- Complete sequencing of the human genome and many other animal and microbial genomes, including their variants, to understand the genetic and environmental basis of normal and abnormal function
- Computational algorithms and databases to predict the tertiary structure of proteins on the basis of amino acid sequences and model systems that predict functionality
- Novel amino acids, codons, proteins, and derivative enzymes that enable improved medical, biological, and industrial uses

Providing Extraordinary Tools for Extraordinary Science

- New accelerator designs, testbeds, and detectors for theoretical particle and nuclear physics, and (as supported by the physics communities) next-generation machines such as the Next Linear Collider, Muon Collider, and advanced, laser-based optical accelerators
- New and upgraded probes and instruments for investigating materials, chemical processes, and life, including the Spallation Neutron Source, now under construction, and fourth-generation light sources such as free electron lasers and femtosecond x-ray lasers
- Parallel-processor supercomputers capable of petaflop speeds (a thousand trillion floating-point operations per second) to serve as powerful platforms for solutions to many complex problems
- New algorithms and powerful software for scientific applications, modeling, and visualization that serve as tools to increase scientific exploration and understanding
- Efficient, powerful networking tools for communication and remote operation of collaboratories for effective, efficient use of DOE's scientific resources by a broader scientific community
- Science education through fellowships in universities and colleges, teacher training for secondary schools, outreach to communities, and broad partnership programs in science and technology

Manage as Stewards of the Public Trust

- Peer review to evaluate all programs managed by the Office of Science
- Advisory boards for all program offices that are representative of a diverse range of institutions, that help coordinate across organizations, and whose recommendations are fully considered and acted upon by the Office of Science
- Integrated safety management systems implemented at all Office of Science laboratories
- Safety performance evaluation systems (within all Office of Science laboratories) in place that benchmark safety and environmental protection against established standards of performance and are available for public review
- Performance-based management systems in place for all programs and within all laboratories under the cognizance of the Office of Science
- A fully electronic distributed environment that facilitates identification, retrieval, and use of scientific information
- An Office of Science management strategy that reviews cost-effectiveness measures, maintains activity–based management control of its operations, and respects constructive partnerships that deliver results
- Scientific facilities constructed at their full scope on schedule and within budget
- Employee development programs that train and reward employees and build and retain a diverse workforce

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ACRONYMS

ANL Argonne National Laboratory
BAPL Bettis Atomic Power Laboratory
BNL Brookhaven National Laboratory
DOE Department of Energy
EML Environmental Measurements Laboratory
FETC Federal Energy Technology Center
INEEL Idaho National Engineering and Environmental Laboratory
TJNAF Thomas Jefferson National Accelerator Facility
KAPL Knolls Atomic Power Laboratory
LANL Los Alamos National Laboratory
LBNL Lawrence Berkeley National Laboratory
LLNL Lawrence Livermore National Laboratory
NBL New Brunswick Laboratory
NREL National Renewable Energy Laboratory
ORISE Oak Ridge Institute for Science Education
ORNL Oak Ridge National Laboratory
PNNL Pacific Northwest National Laboratory
PPPL Princeton Plasma Physics Laboratory
SNL Sandia National Laboratory

Strategic Framework and Major Programs of the Office of Science

This Strategic Plan supports five goals and 15 more specific objectives that advance the missions of the Office of Science and the Department of Energy. The goals, objectives, and strategies described in the Plan are implemented through a portfolio of research that is supported and managed by the major research programs of the Office of Science. The multidisciplinary nature of this framework is evident in the major contributing programs that support each objective of the Plan, as summarized below and described in greater detail in the accompanying report, the *Science Portfolio*.

- **Fuel the Future** — *Science for Clean and Affordable Energy*
  - New Fuels: BES, BER
  - Clean and Affordable Power: BES, FES
  - Efficient Energy Use: BES
- **Protect Our Living Planet** — *Energy Impacts on People and the Biosphere*
  - Sources and Fate of Energy By-products: BES, BER
  - Impacts on People and the Environment: BER
  - Prevention and Protection: BES, BER
- **Explore Matter and Energy** — *Building Blocks from Atoms to Life*
  - Components of Matter: HEP, NP, BES, BER
  - Origin and Fate of the Universe: HEP, NP
  - Complex Systems: BES, BER, FES, ASCR
- **Provide Extraordinary Tools for Extraordinary Science** — *National Assets for Multidisciplinary Research*
  - Instrumentation for the Frontiers of Science: All SC
  - Scientific Simulation: All SC
  - Institutional Capacity: All SC
- **Manage as Stewards of the Public Trust** — *Scientific and Operational Excellence*
  - Scientific Excellence and Mission Relevance: All SC
  - Protect Workers, the Public, and the Environment: All SC
  - Management Effectiveness and Efficiency: All SC

ASCR=Advanced Scientific Computing Research **BES**=Basic Energy Sciences **FES**=Fusion Energy Sciences
HEP=High Energy Physics **NP**=Nuclear Physics **SC**=Office of Science